SUSY (with explaining $(g-2)_\mu$) at the LHC

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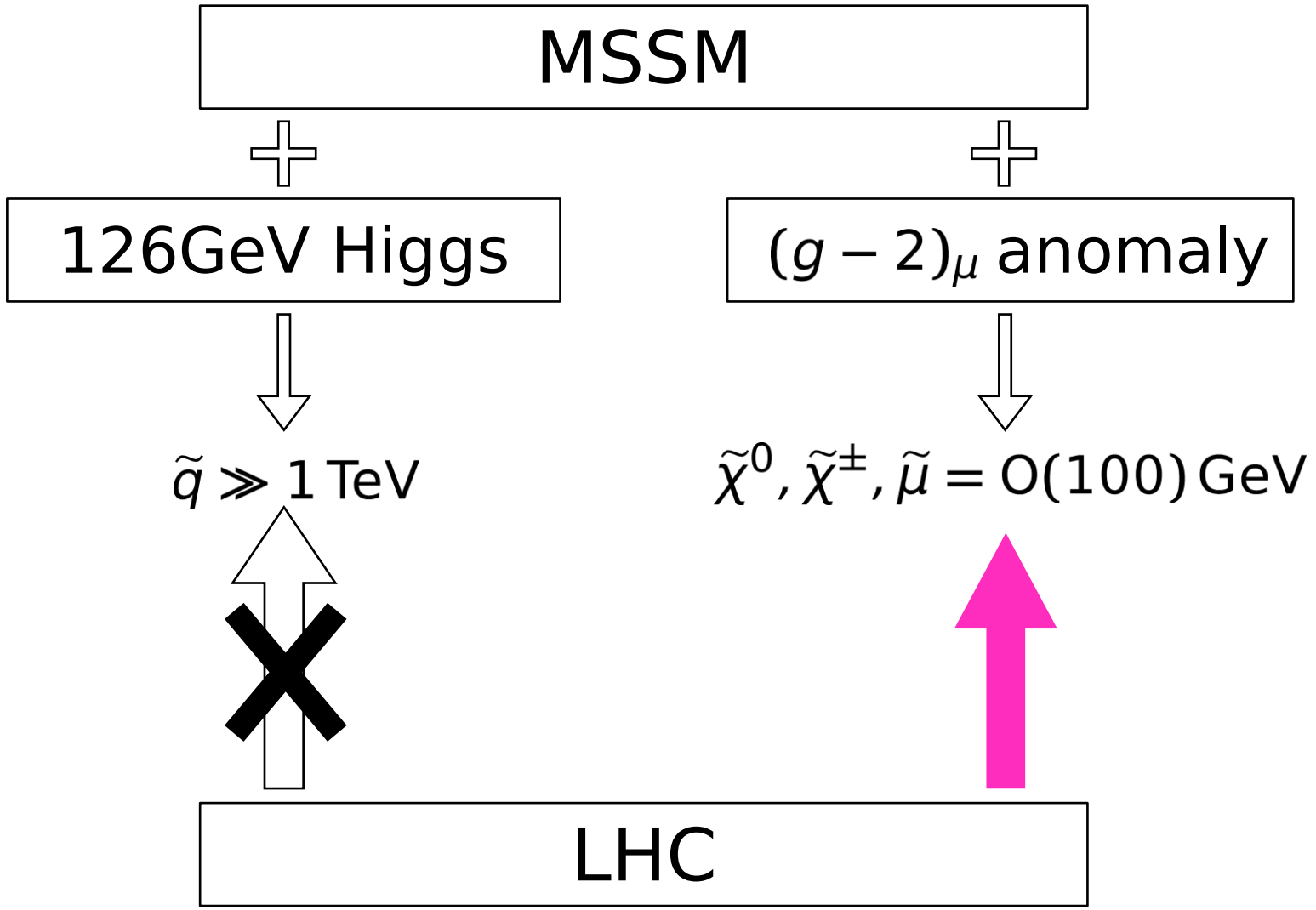
References

Endo, Hamaguchi, SI, Yoshinaga [1203.4256].

Endo, Hamaguchi, SI, Yokozaki [1108.3071][1112.5653][1202.2751];
Endo, Hamaguchi, Ishikawa, SI, Yokozaki [1212.3935].

Topic 1. (Minimal SUSY Standard Model)



Topic 2.

(Minimal SUSY Standard Model)

MSSM

＋ ＋

126GeV Higgs

$(g-2)_\mu$ anomaly

⇓ ⇓

$\tilde{q} \gg 1\,\mathrm{TeV}$ ⟷ $\tilde{\chi}^0, \tilde{\chi}^\pm, \tilde{\mu} = \mathrm{O}(100)\,\mathrm{GeV}$

tension

ex) mGMSB cannot generate such spectra.

(minimal Gauge-Mediated SUSY-breaking)

LHC

Topic 2.

(Minimal SUSY Standard Model)

MSSM **+ vector-like quarks**

126GeV Higgs

$(g-2)_\mu$ anomaly

$\tilde{q} \sim 1\,\mathrm{TeV}$ ⟷ $\tilde{\chi}^0, \tilde{\chi}^\pm, \tilde{\mu} = \mathrm{O}(100)\,\mathrm{GeV}$

resolved

~~**tension**~~

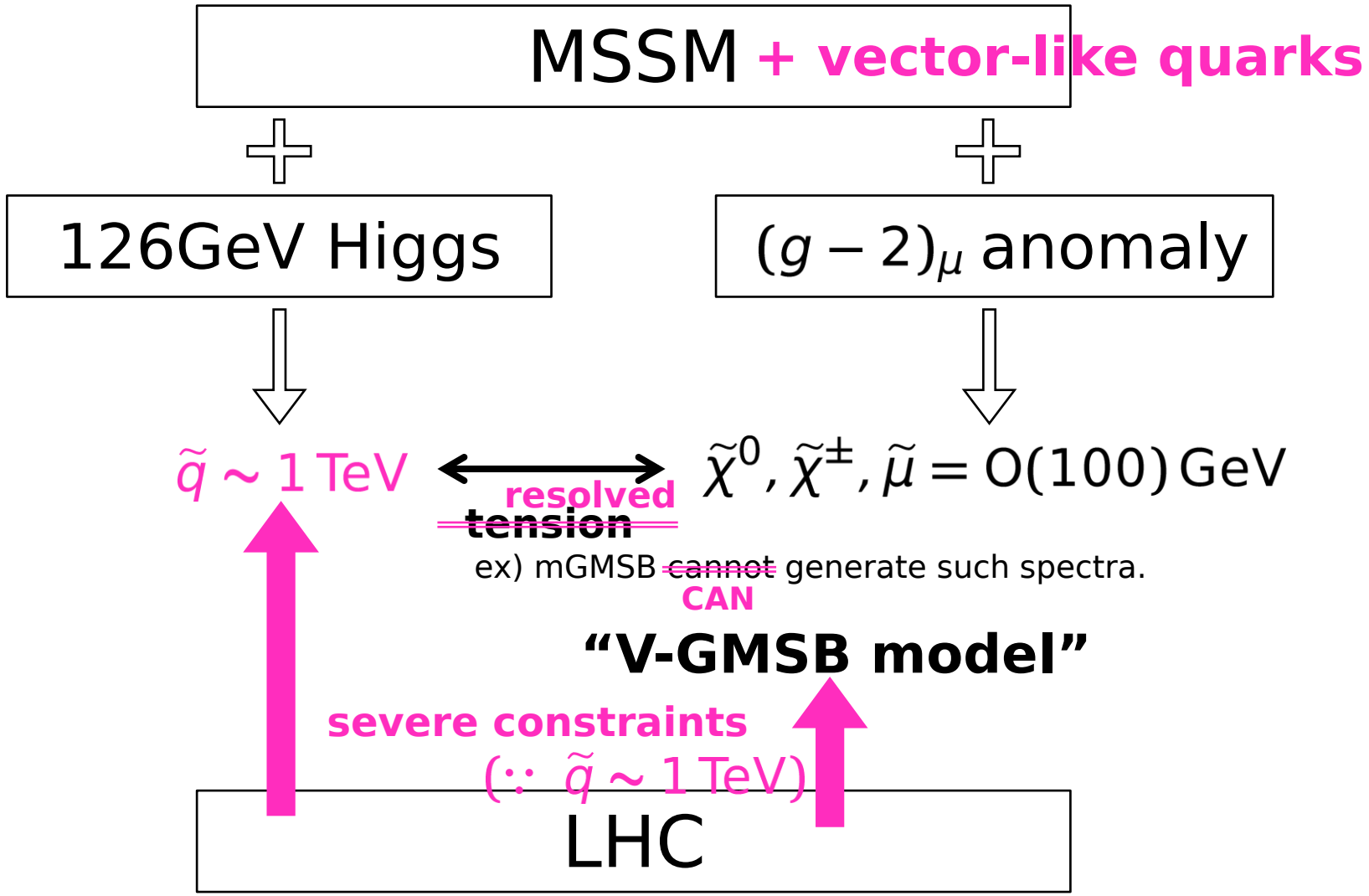
ex) mGMSB ~~cannot~~ **CAN** generate such spectra.

"V-GMSB model"

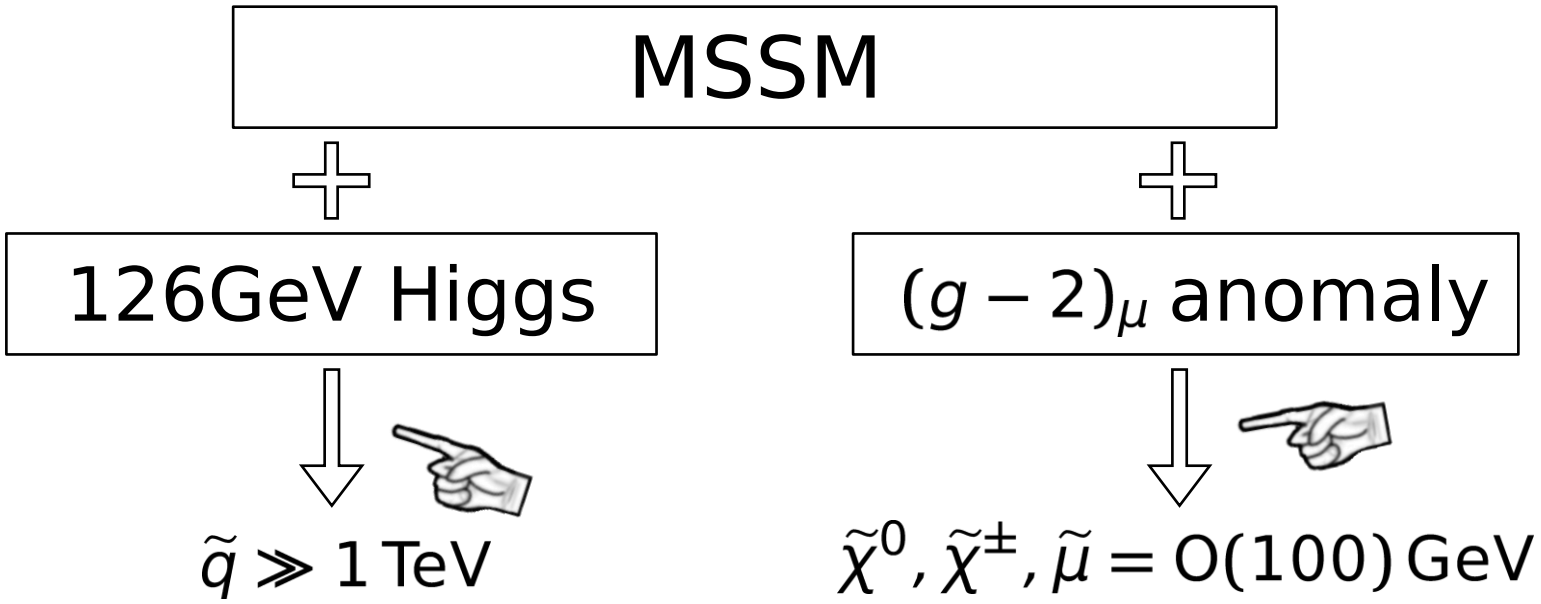
LHC

Topic 2.

(Minimal SUSY Standard Model)



1. **Foundation**



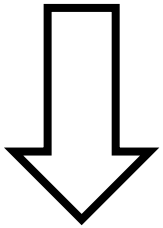
2. **Topic 1)** $\tilde{\chi}^0, \tilde{\chi}^\pm, \tilde{\mu}$ **direct-search**

3. **Topic 2) V-GMSB model**

[(MSSM + vector-like quarks) + GMSB]

Standard Model Now Completed!

- Problems
  - Hierarchy Problem, muon $g-2$ anomaly, …
- Anxiety towards ultimate theory



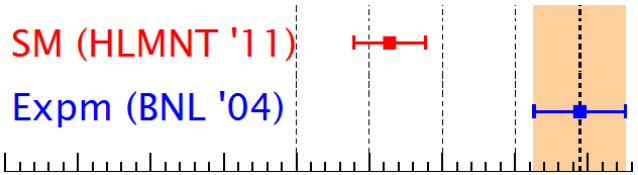
Supersymmetry (SUSY)

MSSM (Minimal SUSY Standard Model)

- hierarchy : solved. (or relaxed.)
- $(g-2)_\mu$ anomaly : explained.
- gauge coupling unification : improved.

$$\left(a_\mu := \frac{g_\mu - 2}{2}\right)$$

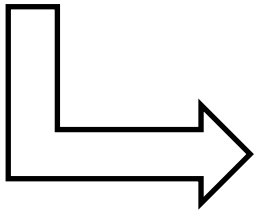
- $(g-2)_\mu$ anomaly



$$a_\mu^{\mathrm{SM}} = (116\,591\,828 \pm 49) \times 10^{-11}$$
$$a_\mu^{\mathrm{exp}} = (116\,592\,089 \pm 63) \times 10^{-11}$$

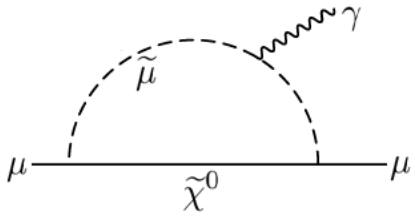
Hagiwara, Liao, Martin, Nomura, Teubner [1105.3149]

3.3σ discrepancy

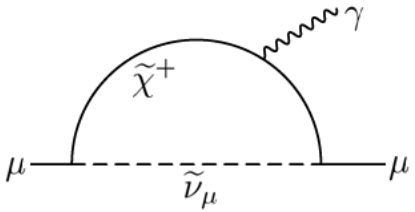


can be explained with **MSSM**
if μ-term > 0, $\tan\beta \gtrsim 10$,
and $m\left(\tilde{\chi}^0, \tilde{\chi}^\pm, \tilde{\mu}, \tilde{\nu}_\mu\right) \sim \mathrm{O}(100)\,\mathrm{GeV}$.

Lopez, Nanopoulos, Wang [ph/9308336]
Chattopadhyay, Nath [ph/9507386]
Moroi [ph/9512396]



$$\Delta a_\mu\left(\tilde{\chi}^0, \tilde{\mu}\right) \approx \frac{g_Y^2}{(4\pi)^2} \frac{m_\mu^2}{m_{\mathrm{soft}}^2} \mathrm{sgn}(\mu) \tan\beta + \cdots,$$



$$\Delta a_\mu\left(\tilde{\chi}^\pm, \tilde{\nu}\right) \approx \frac{g_2^2}{(4\pi)^2} \frac{m_\mu^2}{m_{\mathrm{soft}}^2} \mathrm{sgn}(\mu) \tan\beta.$$

$W \ni \mu H_{\mathrm{u}} H_{\mathrm{d}}$ (Higgsino mass term), $\quad \tan\beta = \dfrac{\langle H_{\mathrm{u}} \rangle}{\langle H_{\mathrm{d}} \rangle}$,

m_{soft} : SUSY-particle mass-scale, $\quad g_i$: Gauge couplings.

tree | one-loop level (top-stop)

$$m_h^2 \approx m_Z^2 + \frac{3 g_W^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} - \frac{(\alpha^2-6)^2}{12} + 3\right]$$

where $\alpha := A_t / m_{\tilde{t}}$.

(stop mixing parameter)

heavier m_h $\Longleftrightarrow$

- $\tilde{t}$ should be *heavy*

  and/or

- stop mixing parameter α at sweet spot ($\sim \pm\sqrt{6}$).

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(stop mixing parameter)

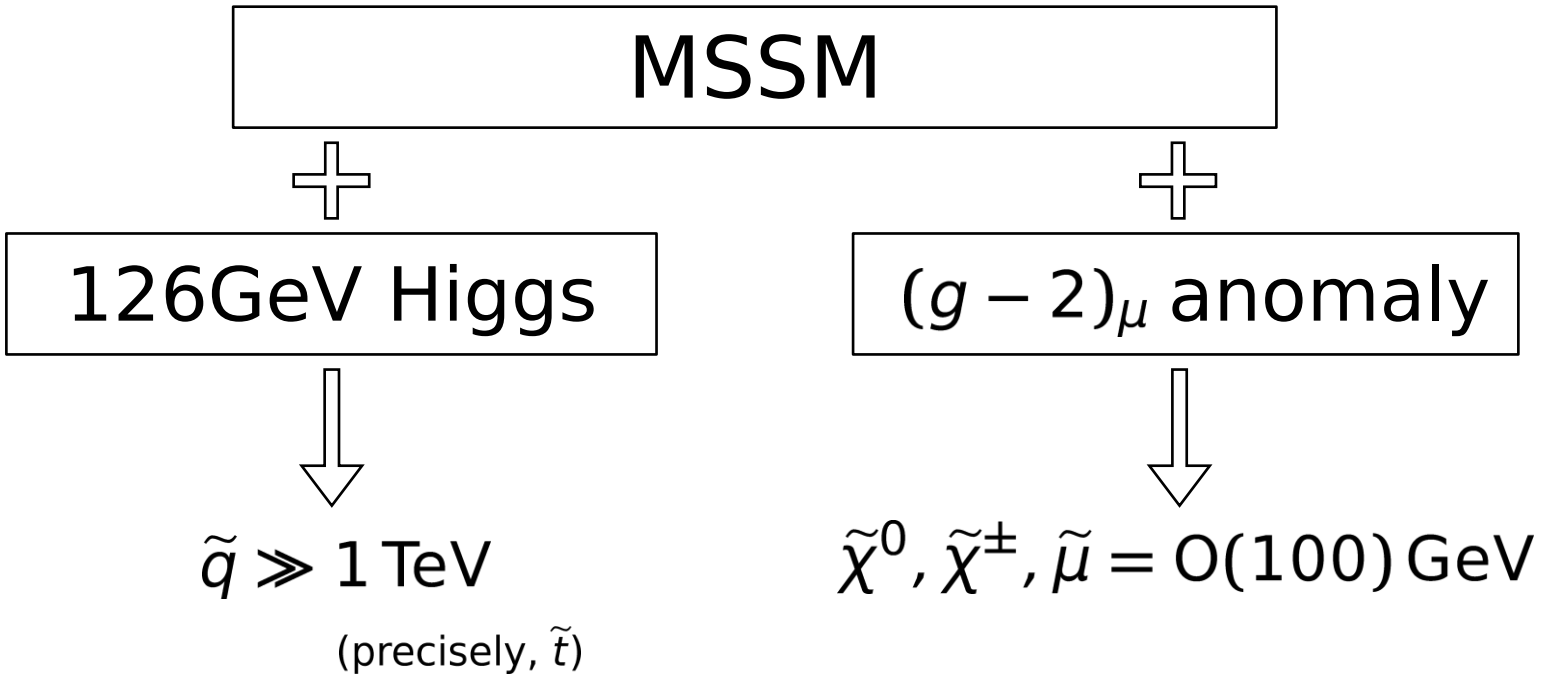
heavier m_h $\Longleftrightarrow$ $m_{\tilde{t}} \sim \begin{cases} 1\text{–}2\,\text{TeV} & (\alpha \sim \pm\sqrt{6}) \\ \text{O}(10)\,\text{TeV} & (\alpha \sim 0) \end{cases}$

Ibe, Yanagida [1112.2462]
Draper, Meade, Reece, Shih [1112.3068]

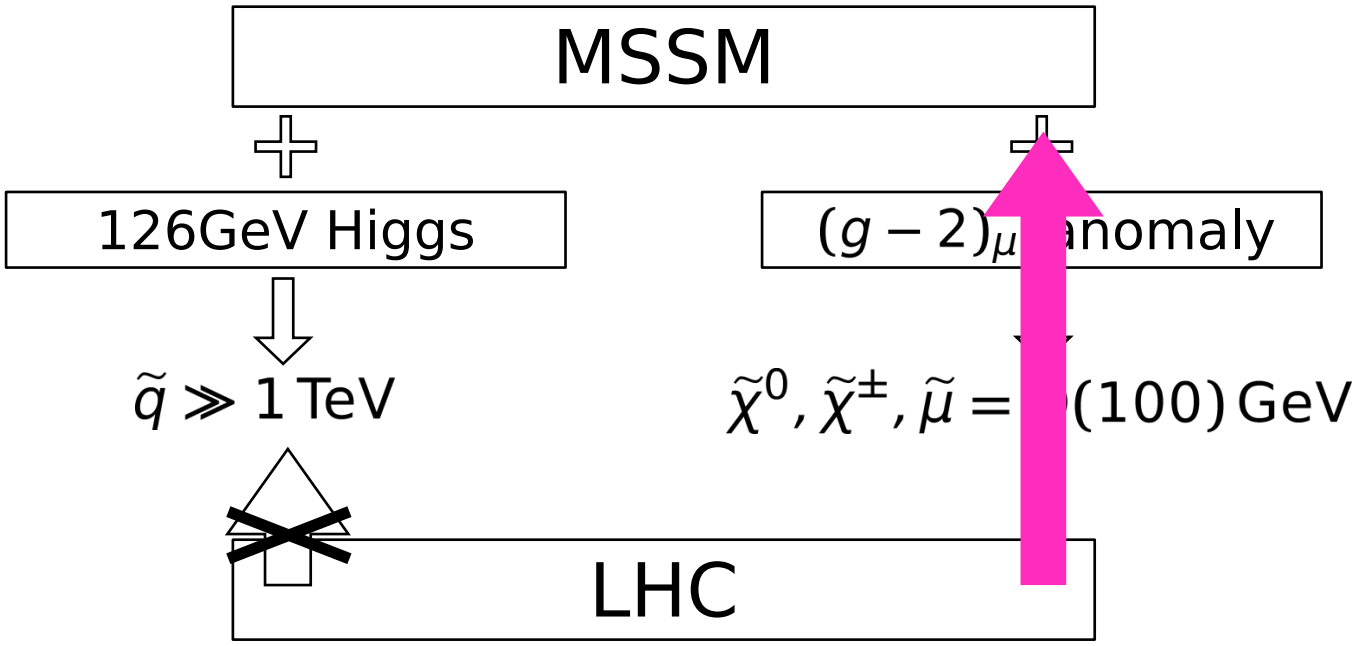
- $\tilde{t}$ should be *heavy*

  and/or

- stop mixing parameter α at sweet spot ($\sim \pm\sqrt{6}$).


MSSM
126GeV Higgs
$(g-2)_\mu$ anomaly
$\tilde{q} \gg 1\,\mathrm{TeV}$
(precisely, $\tilde{t}$)
$\tilde{\chi}^0, \tilde{\chi}^\pm, \tilde{\mu} = \mathrm{O}(100)\,\mathrm{GeV}$

Topic 1 : SUSY search respecting $(g-2)_\mu$



Where's SUSY?

- $m_h = 126$ GeV ⇨ $m_{\tilde{t}} = \mathrm{O}(1\text{–}10)\,\mathrm{TeV}$?
- Nothing@LHC ⇨ $m(\tilde{q}, \tilde{g}) \gtrsim 1\,\mathrm{TeV}$.

Colored = Heavy !?

⇩

Non-colored Search!!!

Many params : $\mu, \tan\beta, m_A; M_1, M_2, m_L^2, m_{\bar{E}}^2, \cdots$

Various targets : $\tilde{e}, \tilde{\mu}, \tilde{\tau}, \widetilde{W}^{\pm}, \ldots$

↳ Use $(g-2)_\mu$ as a guide.

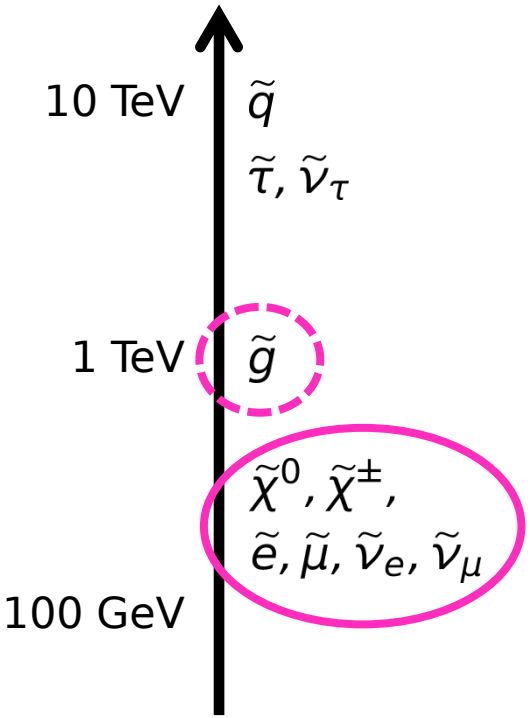
$(g-2)_\mu$-motivated MSSM

All params are input @ TeV-scale. (PMSSM)

MODEL INDEPENDENT!!

- squarks & stau $(\tilde{\tau}, \tilde{\nu}_\tau)$: **HEAVY**
  ↑(to simplify LHC analyses)
- sleptons & $\tilde{\chi}^0, \tilde{\chi}^\pm \sim \mathrm{O}(100)\,\mathrm{GeV}$
  - sleptons: $(\tilde{e}, \tilde{\nu}_e) = (\tilde{\mu}, \tilde{\nu}_\mu)$ $\left[\ll (\tilde{\tau}, \tilde{\nu}_\tau)\right]$
  - gauginos: $M_1 : M_2 : M_3 = 1 : 2 : 6.$
    (approximate GUT relation)

- A-terms $= 0$
- $\tan\beta = 40$
- $m_A = 1500\,\mathrm{GeV}$ ($B_s \to \mu\mu$ constr. satisfied.)
- $m_h = 126\,\mathrm{GeV}$ is assumed. ($\because$ $\tilde{q}$ are decoupled.)
- R-parity conserved.



Search targets

Rest Params: $(m_L^2, m_{\bar{E}}^2)$: slepton soft-masses

(M_2, μ) : gaugino/Higgsino mass

Rest Params: $(m_L^2, m_{\tilde{E}}^2)$: slepton soft-masses

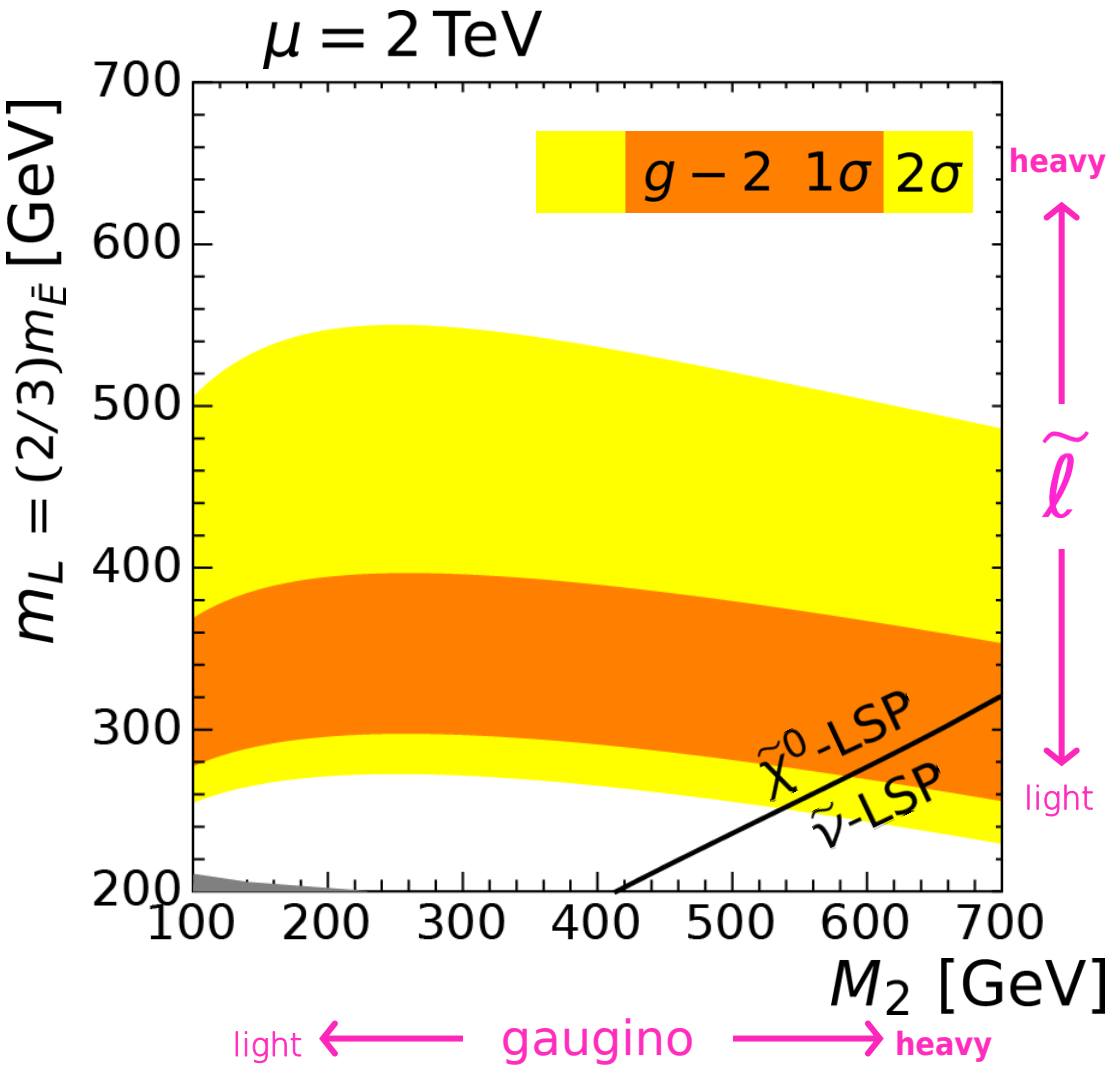
(M_2, μ) : gaugino/Higgsino mass

Two extreme cases

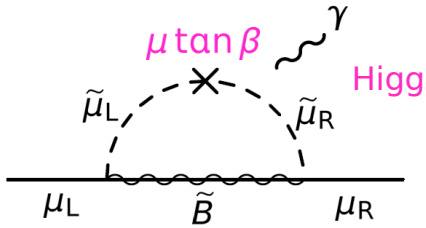
- $\tilde{\mu}_R$-decoupled case ($m_{\tilde{E}}^2 = (3\,\mathrm{TeV})^2$)
- $\tilde{h}$-decoupled case ($\mu = 2\,\mathrm{TeV}$)

- Current Limit
- Future Prospects

An extreme case: $\mu = 2\,\text{TeV}$, $m_L^2 : m_{\bar{E}}^2 = 1 : (1.5)^2$



- $(g-2)_\mu$ dominant source:



Higgsino-free!

- Parameters:
  - $M_1 : M_2 : M_3 = 1 : 2 : 6$
  - $\mu = 2\,\text{TeV}$
  - $m_L^2 : m_{\bar{E}}^2 = 1 : (1.5)^2$
  - $(\tan\beta, m_A) = (40, 1.5\,\text{TeV})$
- Soft-params set @ 7 TeV ($= m_{\tilde{t}}$).
- R-parity conserved.
- LSP is long-lived.
- squark/stau decoupled.
- slepton 1st-gen = 2nd-gen.
- A-terms = 0.

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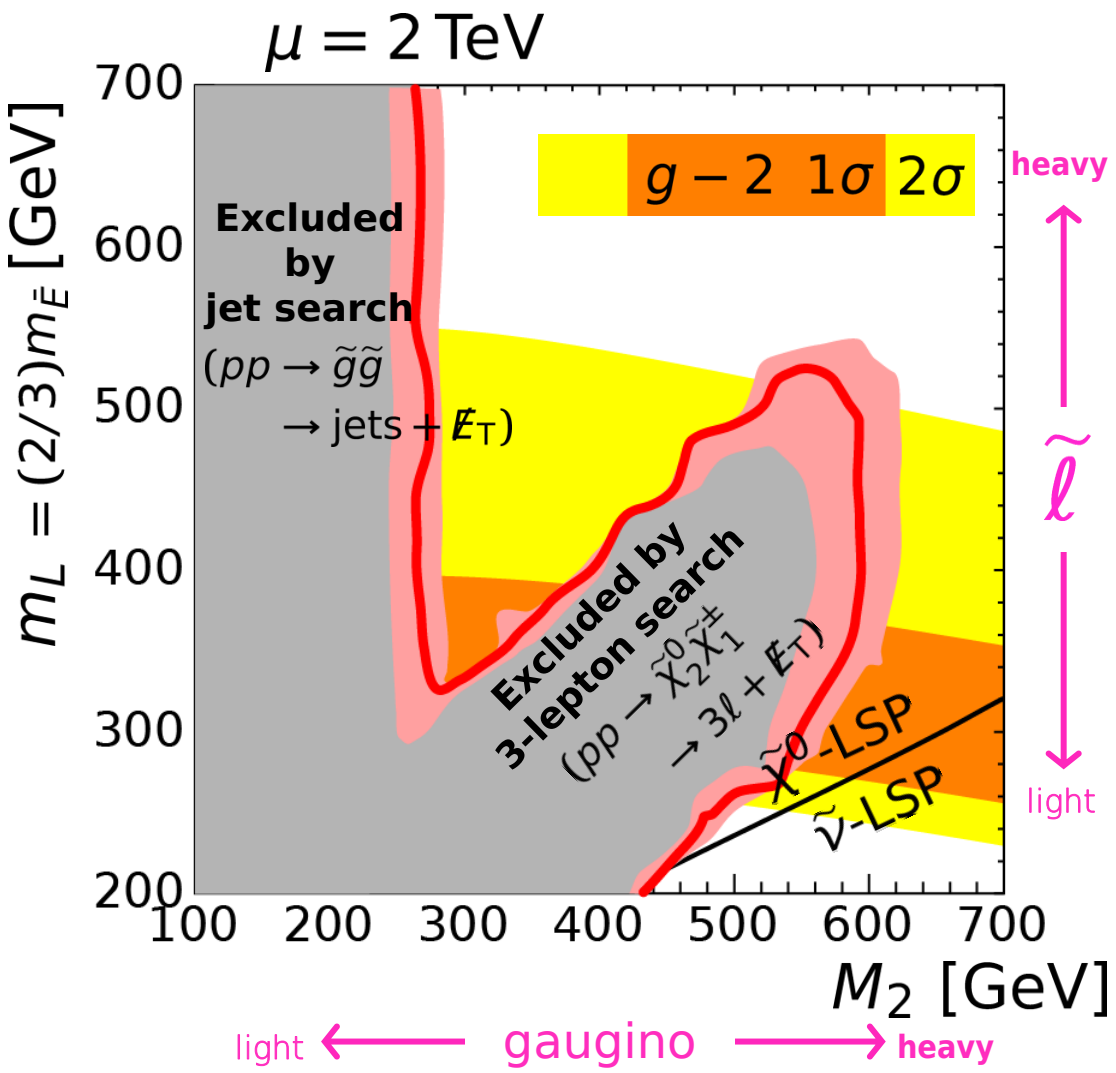

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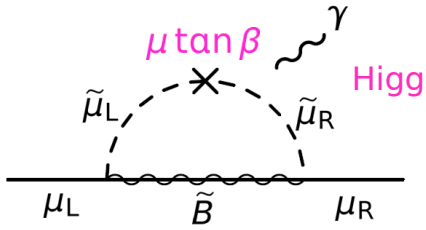

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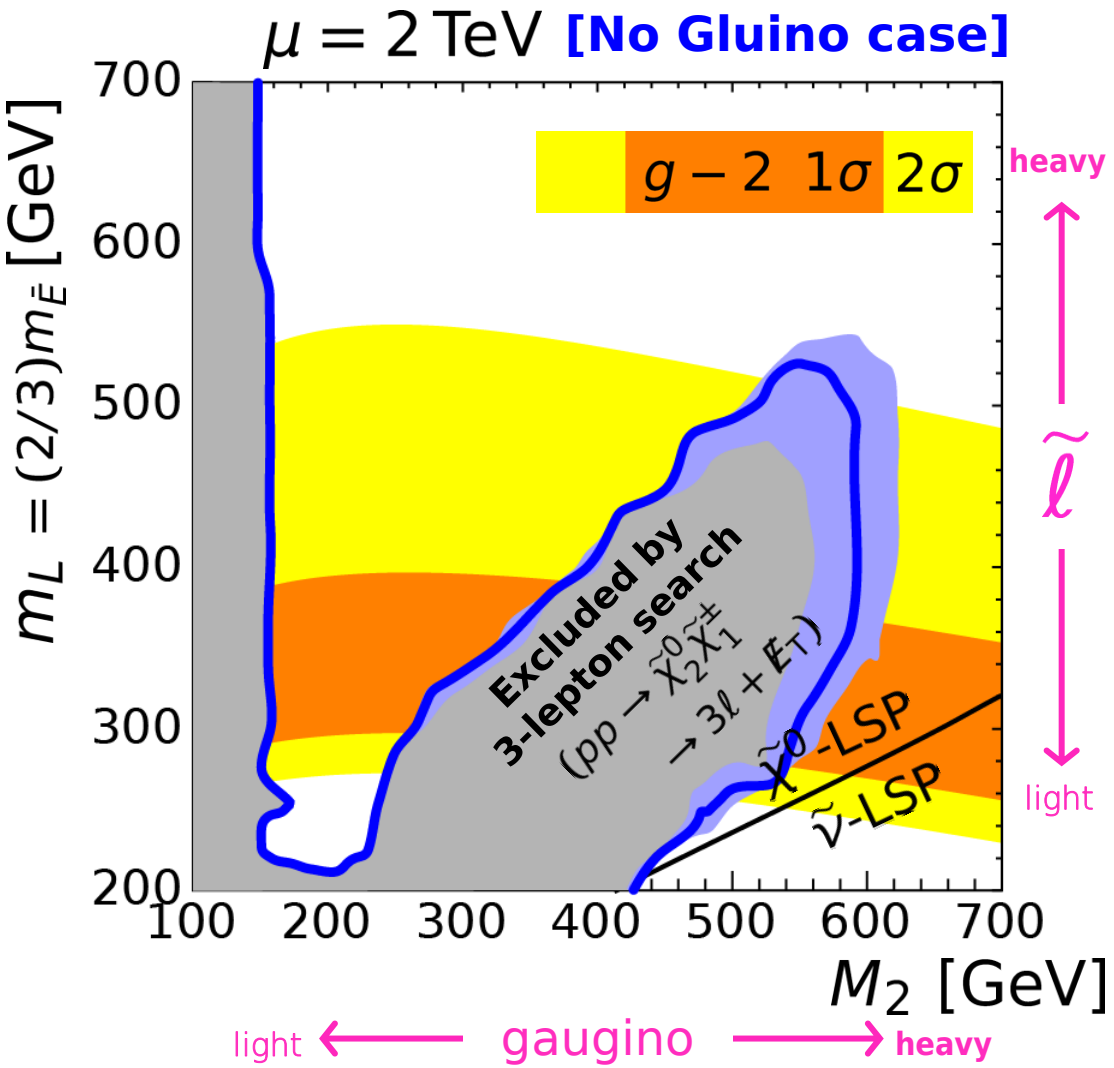

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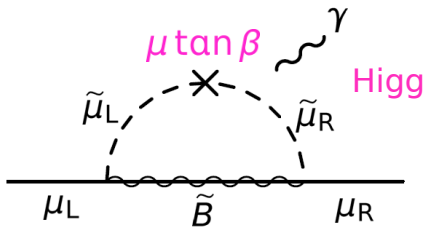

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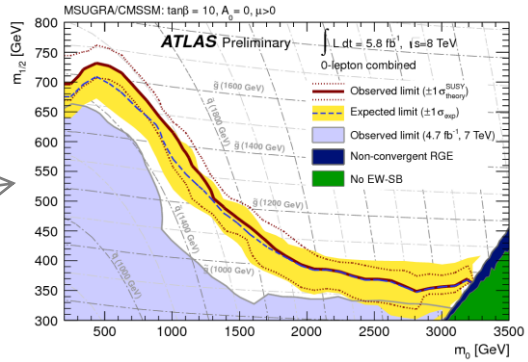
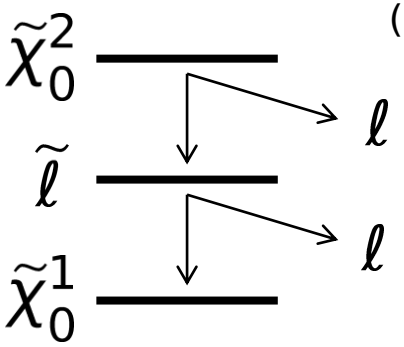
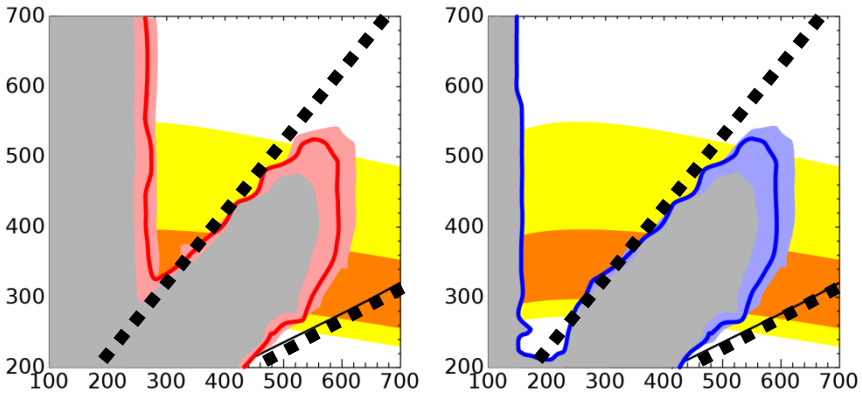
- **jet search** ($pp \to \tilde{g}\tilde{g} \to \text{jets} + \not{E}_T$)
  - ATLAS 8TeV 5.8fb^{-1} [ATLAS-CONF-2012-109]
  - 2-6 hard jets + no lepton + $\not{E}_T$
  - Original bound : $\tilde{g} \gtrsim 950\,\text{GeV}$ (CMSSM, $\tilde{q} \gg \tilde{g}$)



$$\Longrightarrow M_2 \gtrsim 300\,\text{GeV} \text{ in our model}$$

- **3-lepton search** ($pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \to 3\ell + \not{E}_T$)
  - ATLAS 8TeV 13fb^{-1} [ATLAS-CONF-2012-154 **(obsolete)**]
  - Exact 3 leptons + $\not{E}_T$ + vetoing SM-like signal
    (no b-jets, no lepton pairs near M_Z, etc…)
  - Degenerated regions are not excluded.
    (near the dotted lines)





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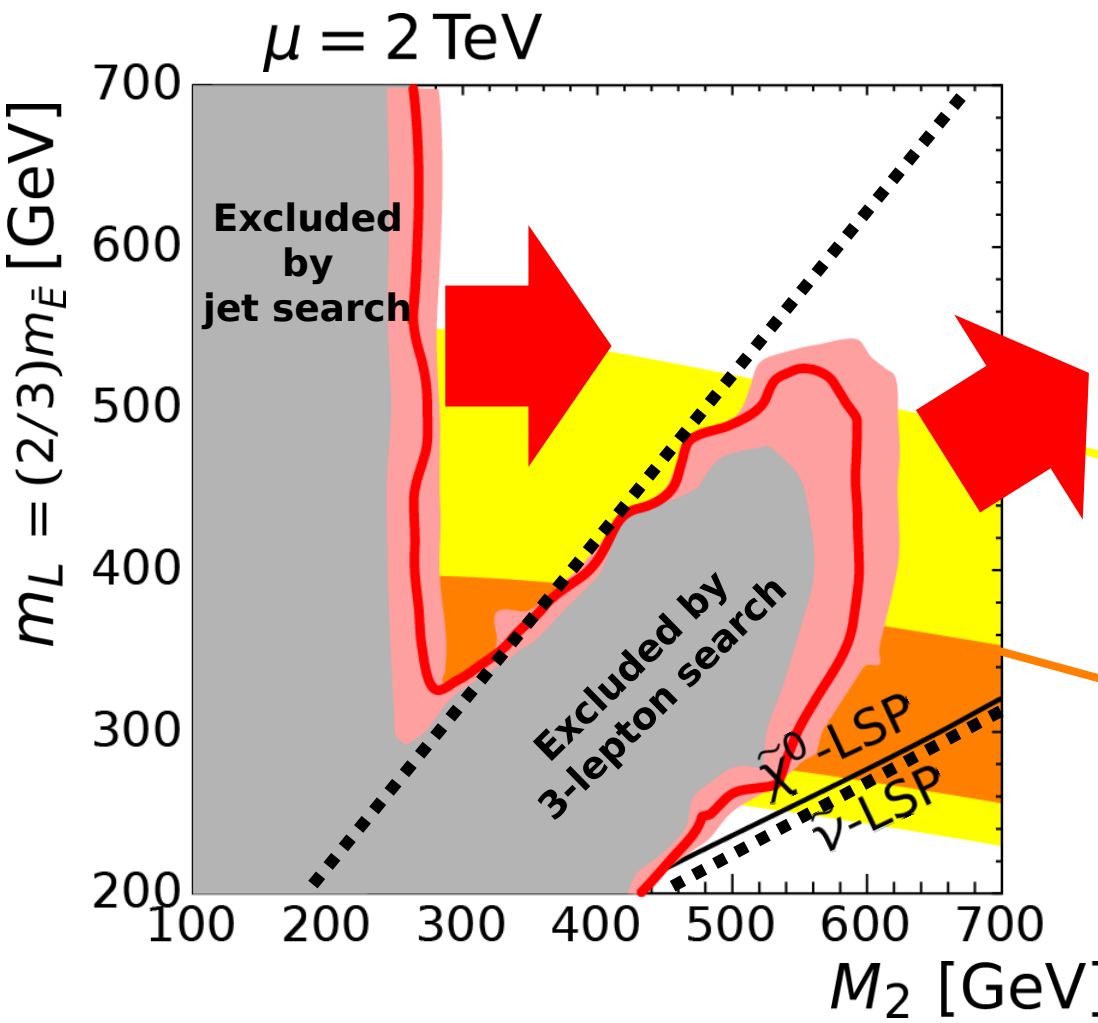
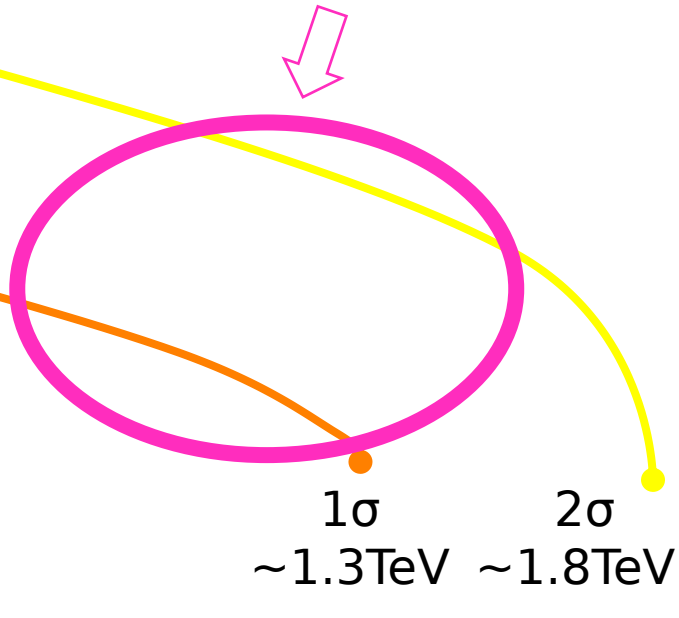


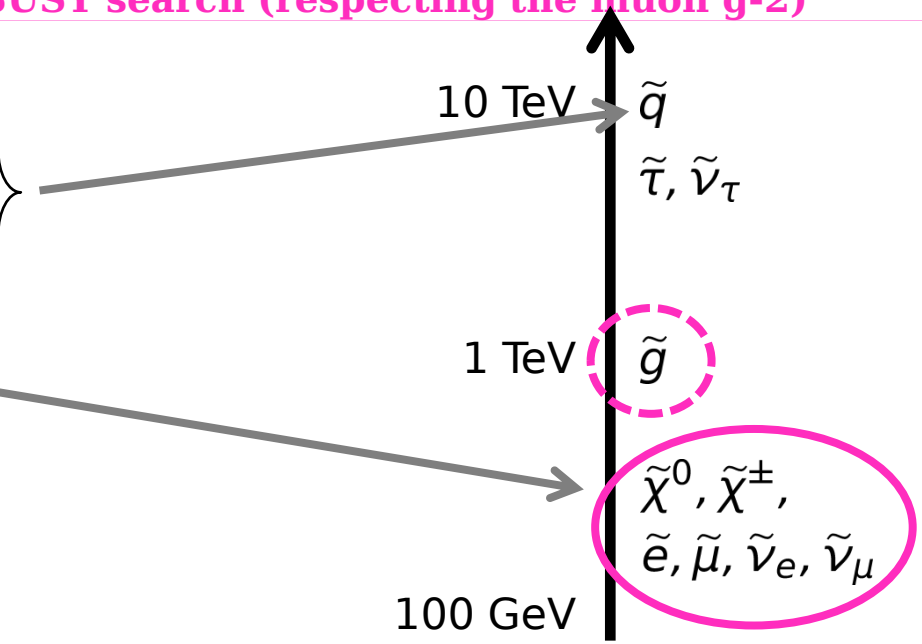
How can we search?

- Heavy gaugino
- Large μ-term
- Light sleptons

... future work.

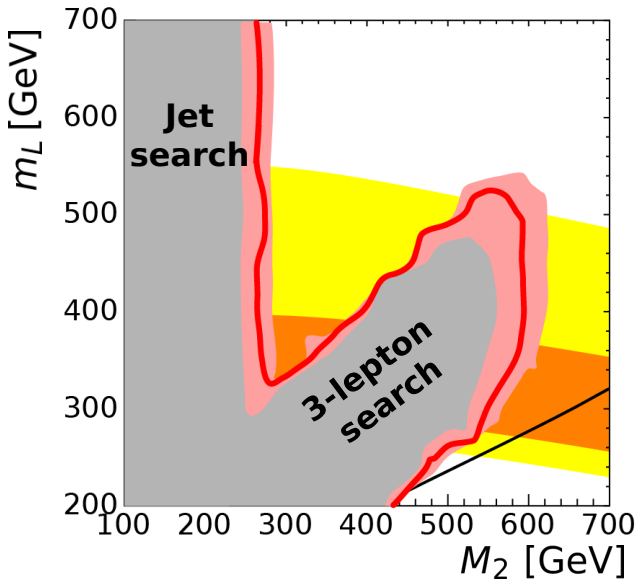


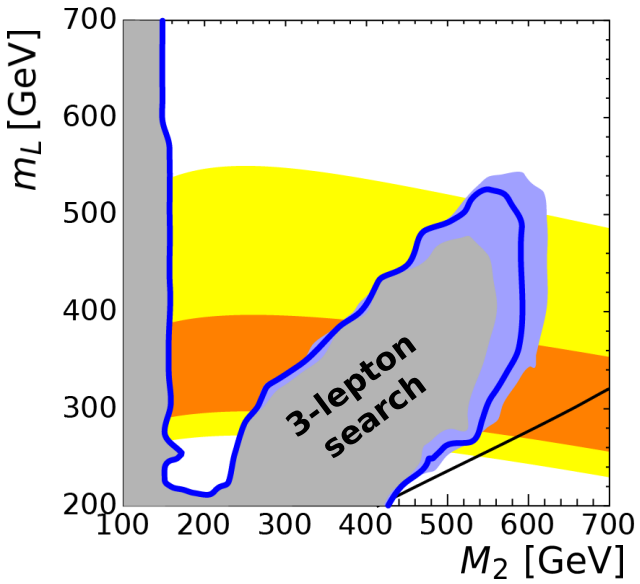
- 126 GeV Higgs
- SUSY Not Found yet
- $(g-2)_\mu$ anomaly



An extreme case: $\mu = 2\,\text{TeV}$, $m_L^2 : m_{\bar{E}}^2 = 1 : (1.5)^2$

Jet: ATLAS-CONF-2012-109
3L: ATLAS-CONF-2012-154





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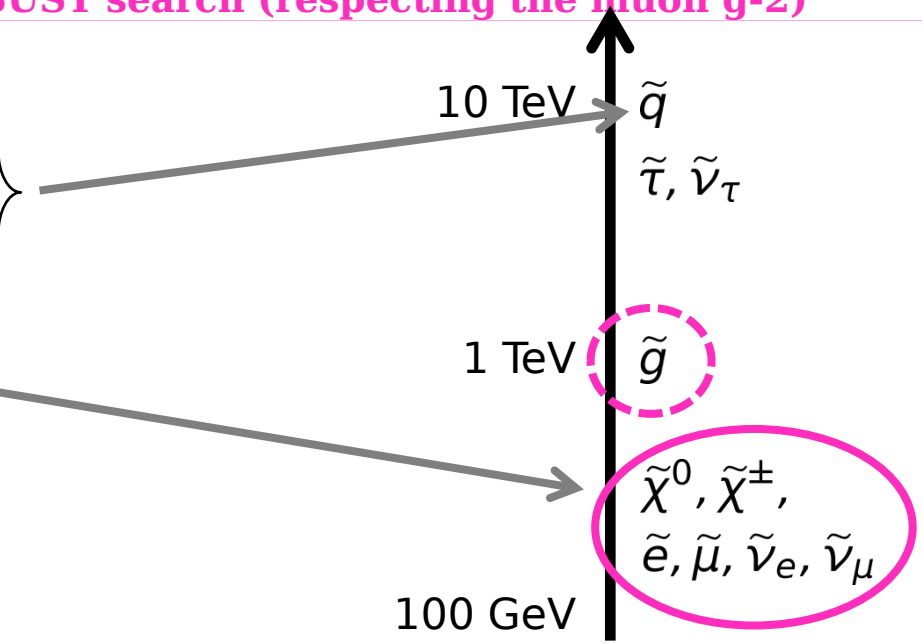

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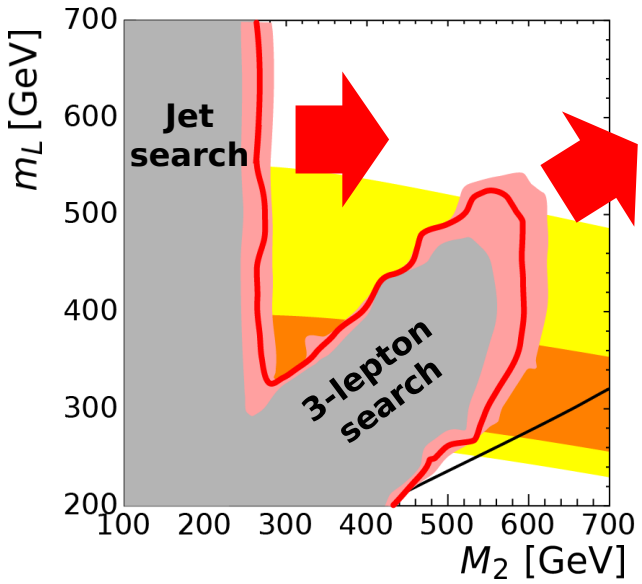

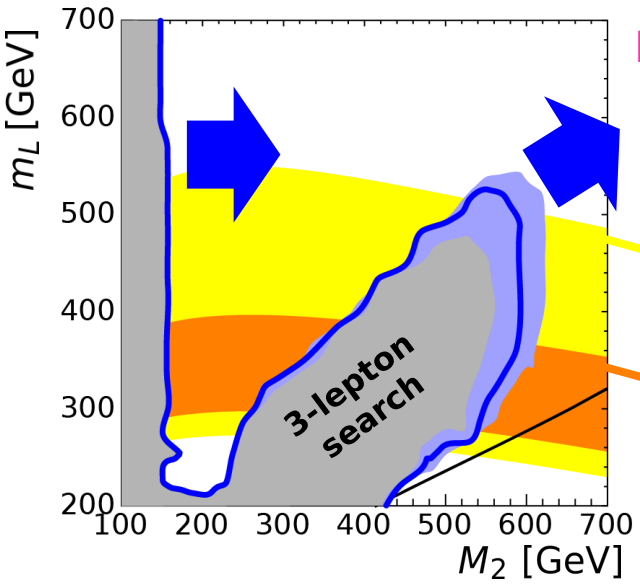

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- Large μ-term
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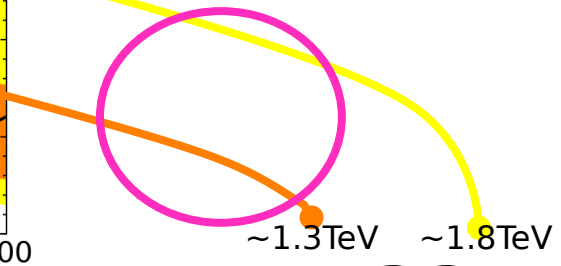
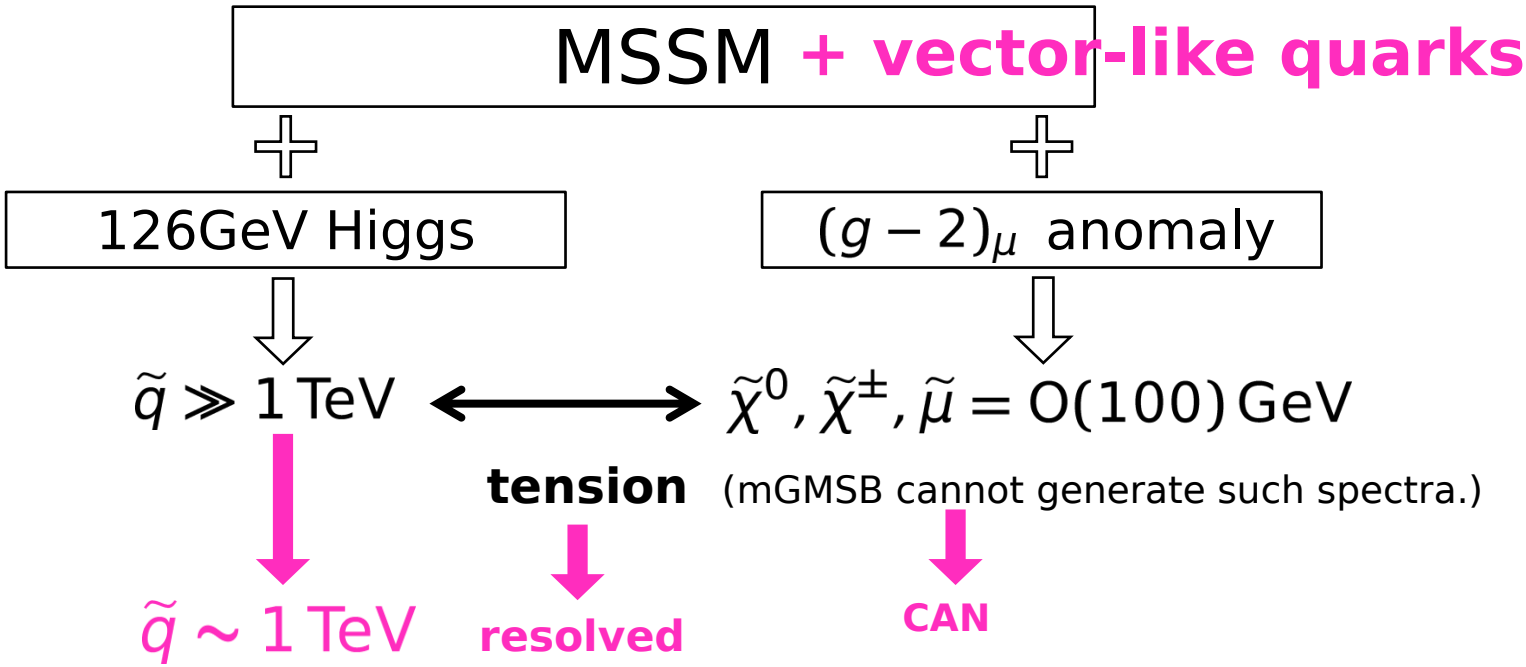
... future work.

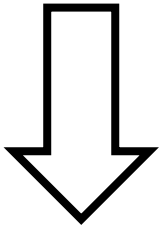


Topic 2 : V-GMSB



MSSM + GMSB (or mSUGRA)

$\Longrightarrow$ $(g-2)_\mu$ with $m_H = 126\,\mathrm{GeV}$



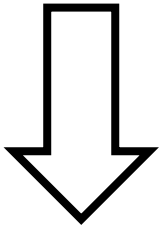
MSSM + **more complicated ~~SUSY~~**

or

Extended model + GMSB/mSUGRA

MSSM + GMSB (or mSUGRA)

$\Longrightarrow$ $(g-2)_\mu$ with ~~$m_h = 126$ GeV~~



MSSM + **more complicated ~~SUSY~~**

or

V-MSSM + GMSB/mSUGRA

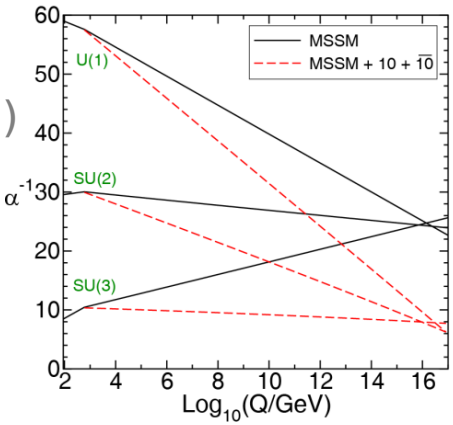
V-MSSM

◉ V-MSSM = MSSM+($\mathbf{10}+\overline{\mathbf{10}}$), i.e. $\begin{cases}\mathbf{10}=(Q',\bar{U}',\bar{E}')\\ \overline{\mathbf{10}}=(\bar{Q}',U',E')\end{cases}$

extra **V**ector-like matters

$$W_{\text{extra}} = Y'Q'H_u\bar{U}' + Y''\bar{Q}'H_dU' \qquad (\text{cf. } W_{\text{MSSM}} \ni Y_tQH_u\bar{U})$$
$$+ M_VQ'\bar{Q}' + M_VU'\bar{U}' + M_VE'\bar{E}'$$
$$W_{\text{mix}} = \epsilon_iQ_iH_uU' + \epsilon'_iQ'H_u\bar{U}_i + \epsilon''_iQ'H_d\bar{D}_i + \epsilon^L_iL_iH_d\bar{E}'$$

- Vector-like ⇨ No gauge anomaly.
- Mixings : necessary (to avoid stable particles)
  but must be tiny. (to avoid large flav-viol.)
- Y' : IR fixed to ~1.05 ⇨ m_h well increased.
- Y'' : reduces m_h ⇨ assumed small.



Martin [0910.2732]

RESULT

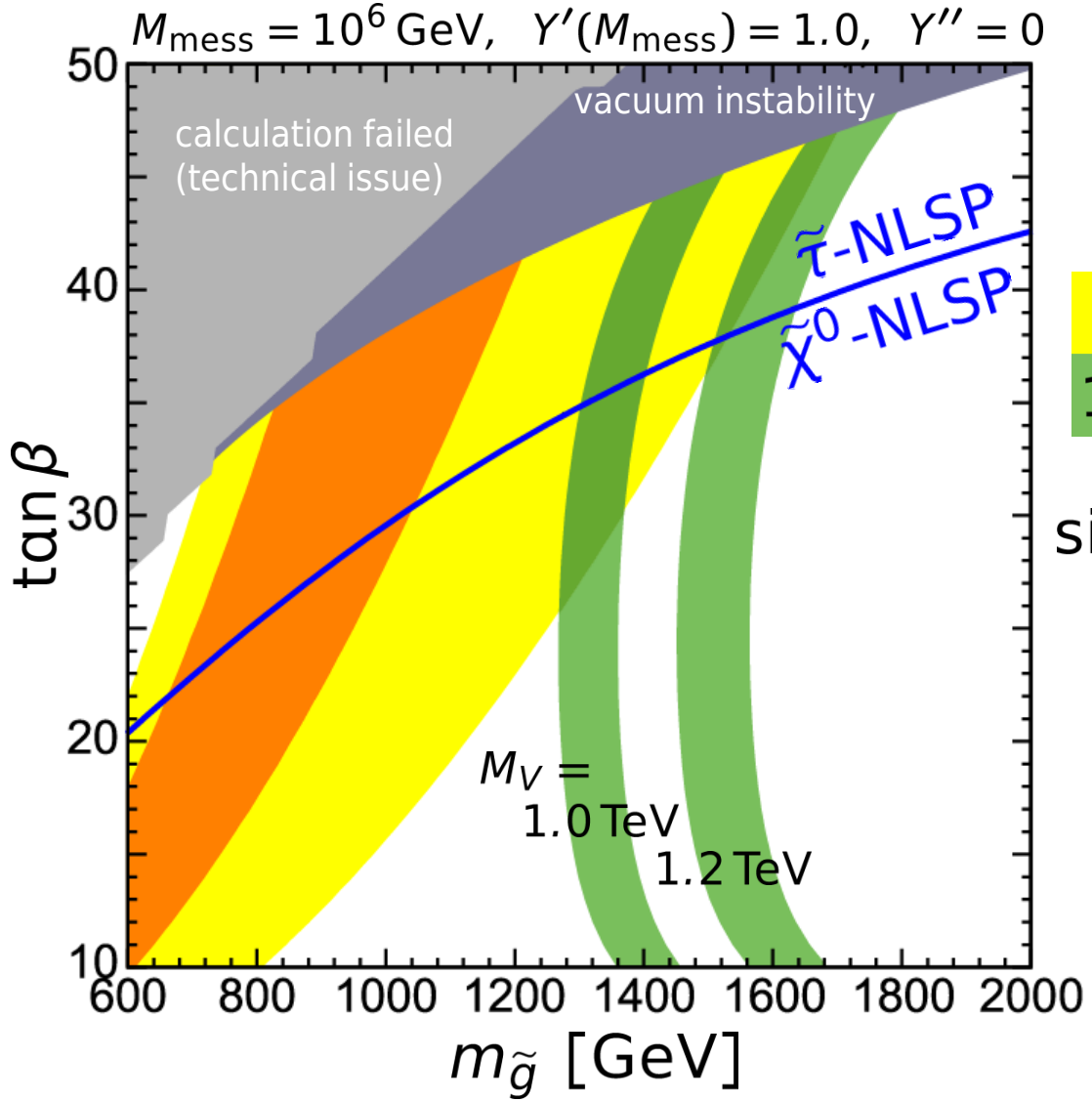
in this talk

with { GMSB framework
mSUGRA framework

→ See [1112.5653]

params: $(\Lambda,\ M_{\rm mess},\ \tan\beta,\ N_{\rm mess},\ {\rm sgn}\,\mu;\ Y',\ M_V)$

$N_{\rm mess} = 1$ + $\Delta(g\text{-}2)>0$; $Y' = 1.0$ (IR fixed)



$g-2$ 1σ 2σ

$125\,{\rm GeV} < m_h < 126\,{\rm GeV}$

simultaneous realization:

$M_V \lesssim 1.2\,{\rm TeV}$,

$m_{\tilde{g}} \lesssim 1.6\,{\rm TeV}$,

$\tan\beta \sim {\rm O}(10)$

➡ **LHC LIMIT!?**

params: $(\Lambda,\ M_{\rm mess},\ \tan\beta,\ N_{\rm mess},\ {\rm sgn}\,\mu;\ Y',\ M_V)$

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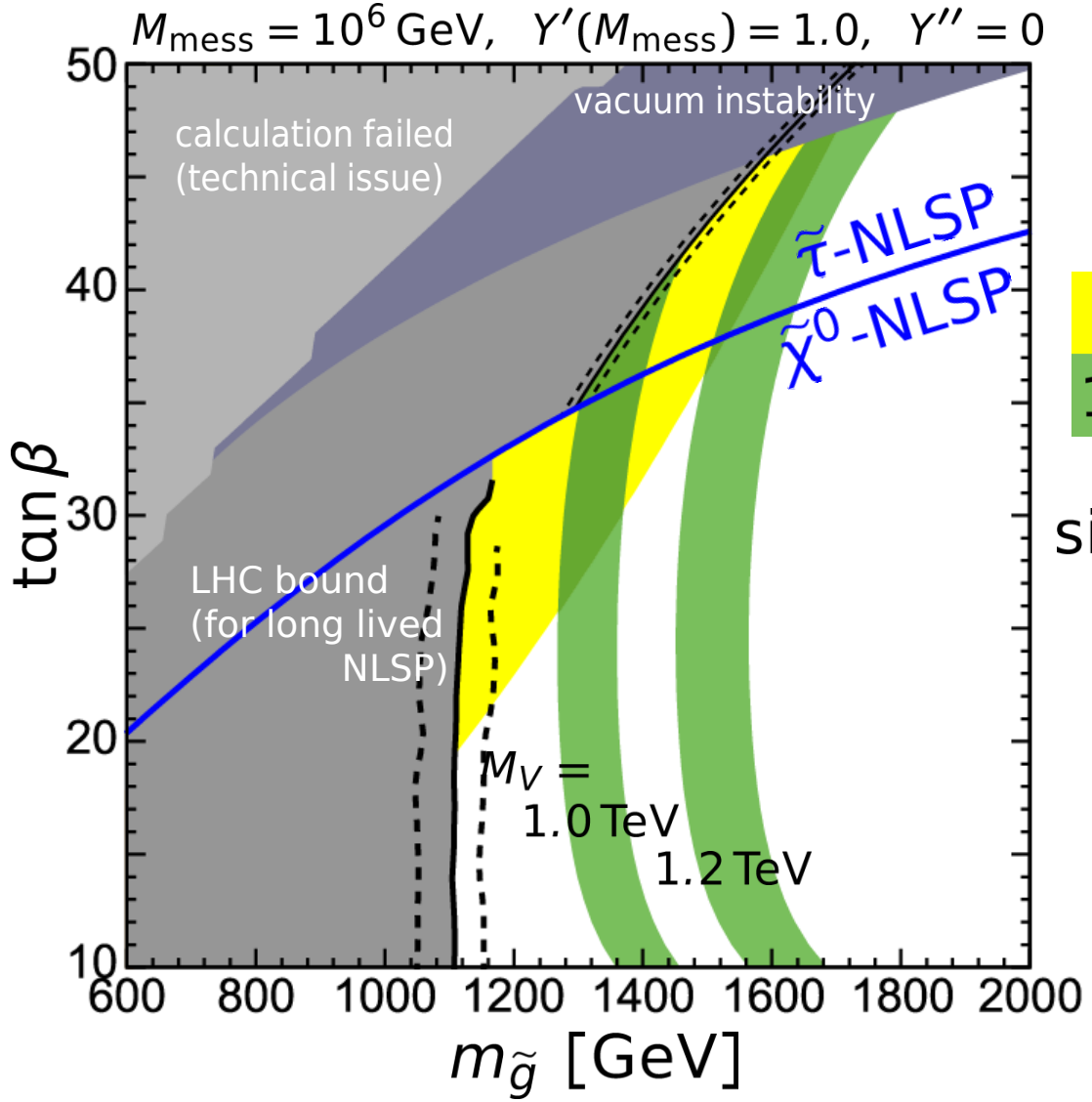

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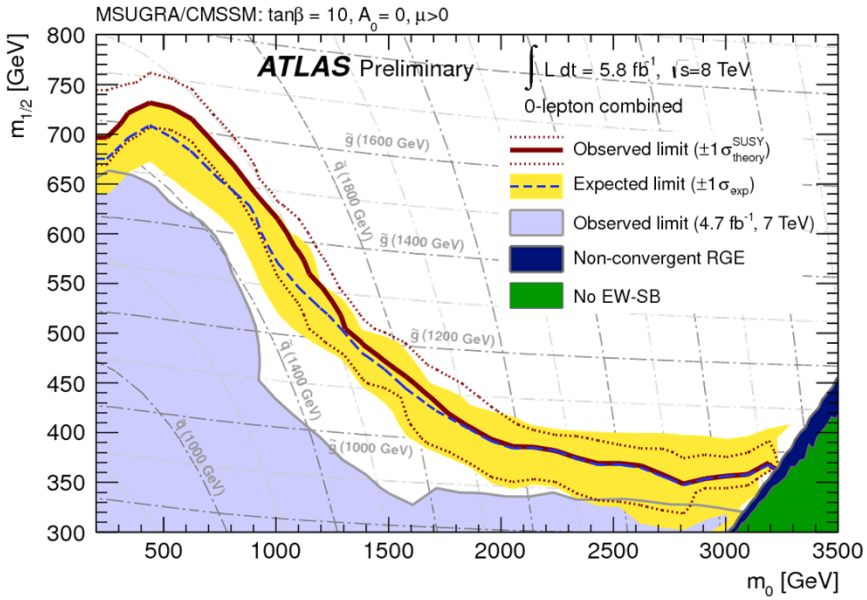
$\tan\beta \sim {\rm O}(10)$

➡ **LHC LIMIT!?**

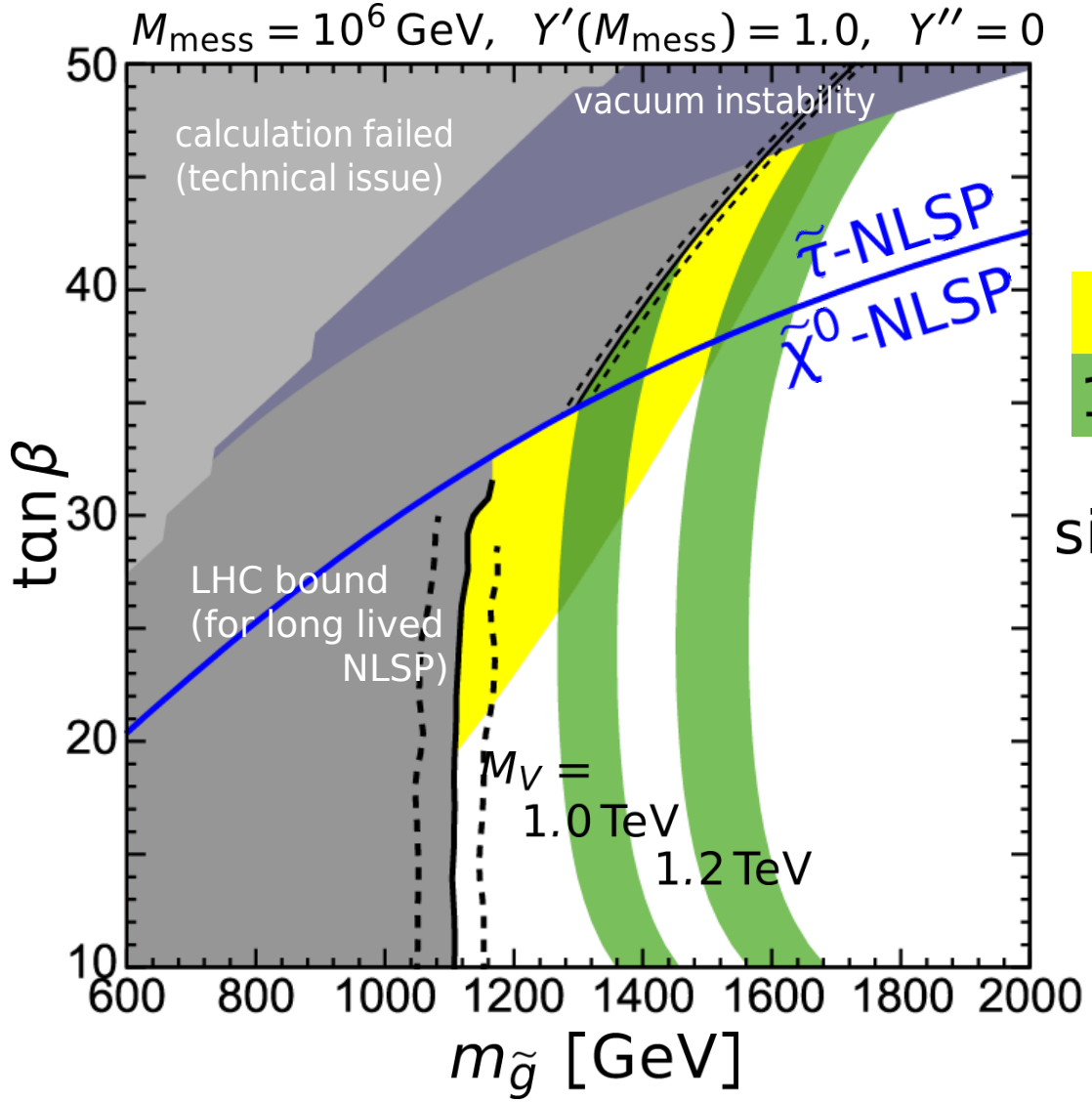
NLSP	Long-lived NLSP	NLSP prompt decay
$\tilde{\chi}_1^0$	jet + $\not{E}_T$ ($\tilde{\chi}_1^0\tilde{\chi}_1^0$) (same as mSUGRA)	jet + $\not{E}_T$ and $2\gamma + \not{E}_T$ (from $\tilde{\chi}_1^0 \to \gamma\tilde{G}$)
$\tilde{\tau}_1$	Long-lived stau	multi-tau

- Our analysis
  - Neutralino NLSP
    → ATLAS 8 TeV-5.8 fb^{-1} (2–6 jets + $\not{E}_T$)
    [ATL-CONF-2012-109]
  - Stau NLSP
    → CMS 7 TeV-5.0 fb^{-1} (assuming $pp \to \tilde{\tau}_1\tilde{\tau}_1^*$)
    $\rightsquigarrow m_{\tilde{\tau}_1} > 223\,\mathrm{GeV}$ [1205.0272]



params: $(\Lambda,\ M_{\rm mess},\ \tan\beta,\ N_{\rm mess},\ {\rm sgn}\,\mu;\ \ Y',\ M_V)$

$N_{\rm mess} = 1$ + $\Delta(g\text{-}2)>0$; $Y' = 1.0$ (IR fixed)



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Appendix

LHC-constraints from

extra-quark search.

MSSM+($\mathbf{10}+\overline{\mathbf{10}}$), i.e. $\begin{cases} \mathbf{10} = (Q', \bar{U}', \bar{E}') \\ \overline{\mathbf{10}} = (\bar{Q}', U', E') \end{cases}$

- $(Q', \bar{U}', \bar{E}') + (\bar{Q}', U', E') \to \left(\tilde{t}'_{1,2,3,4}, \tilde{b}'_{1,2}, \tilde{\tau}'_{1,2}\right)$
  $\& \left(t'_1, t'_2, b', \tau'\right)$

  - Mass

    $m_{t'} \sim M_V \pm (174\,\mathrm{GeV}/2)$,

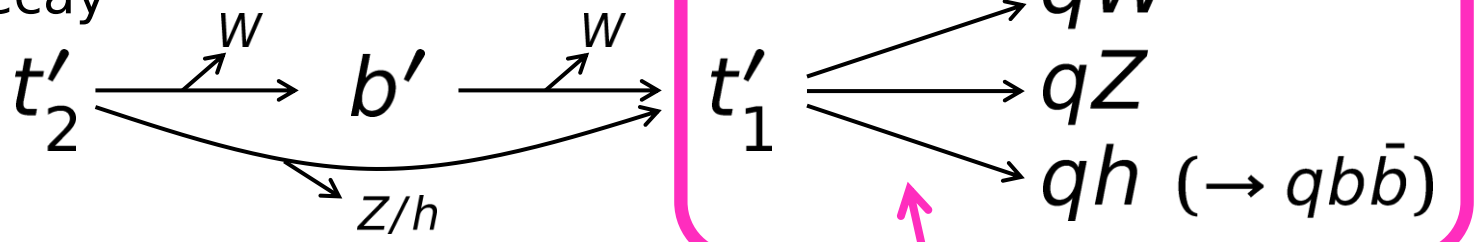
    $m_{b'} = m_{\tau'} = M_V$

$$W_{\mathrm{extra}} = Y' Q' H_u \bar{U}' + M_V Q' \bar{Q}' + M_V U' \bar{U}' + M_V E' \bar{E}'$$
$$W_{\mathrm{mix}} = \epsilon_i Q_i H_u U' + \epsilon'_i Q' H_u \bar{U}_i + \epsilon''_i Q' H_d \bar{D}_i + \epsilon^L_i L_i H_d \bar{E}'$$

  - Production

    $pp \to t'_1 \bar{t}'_1$ etc. (pair production)

  - Decay



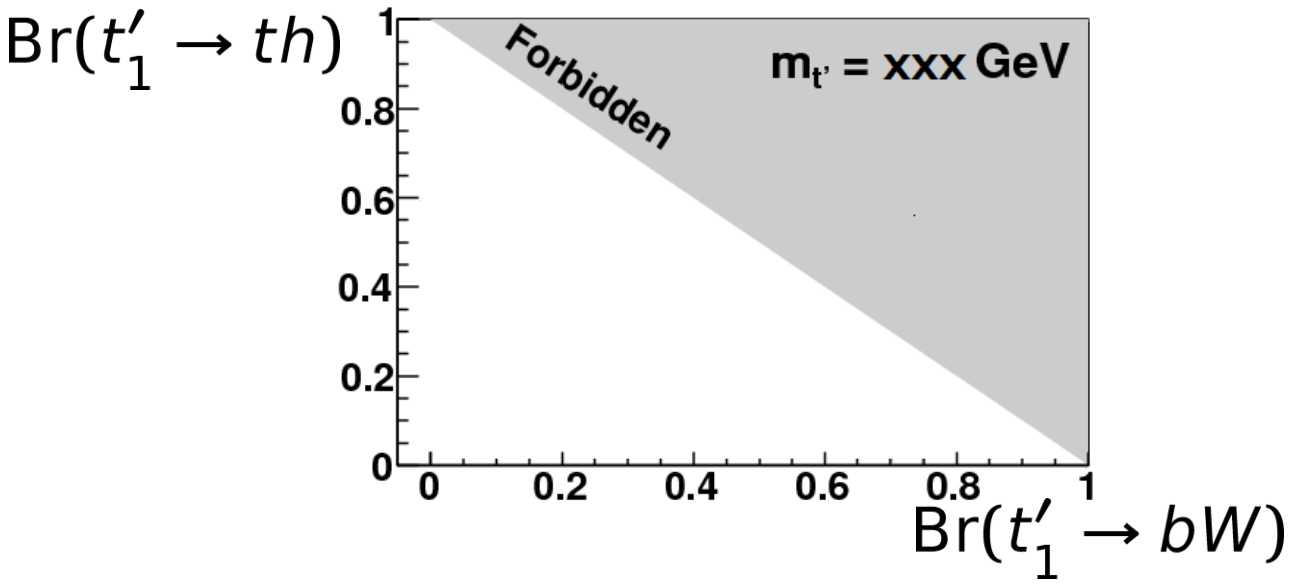
depending on mixing
btw. vec-like/SM quarks.

$$W_{\mathrm{mix}} = \epsilon_i Q_i H_u U' + \epsilon'_i Q' H_u \bar{U}_i + \epsilon''_i Q' H_d \bar{D}_i + \epsilon^L_i L_i H_d \bar{E}'$$

- Assumption: mixing with **3-gen.** only. ($\epsilon_1 = \epsilon_2 = 0$) etc.

$t'_1 \to bW, tZ, th$ ×2 (pair-prod.)

- $bW \to$ b-jet + (0–2)leptons ← Analyzed by ATLAS!!
- $tZ \to$ b-jet + many leptons
- $th \to$ many b-jets ← Analyzed by ATLAS!!



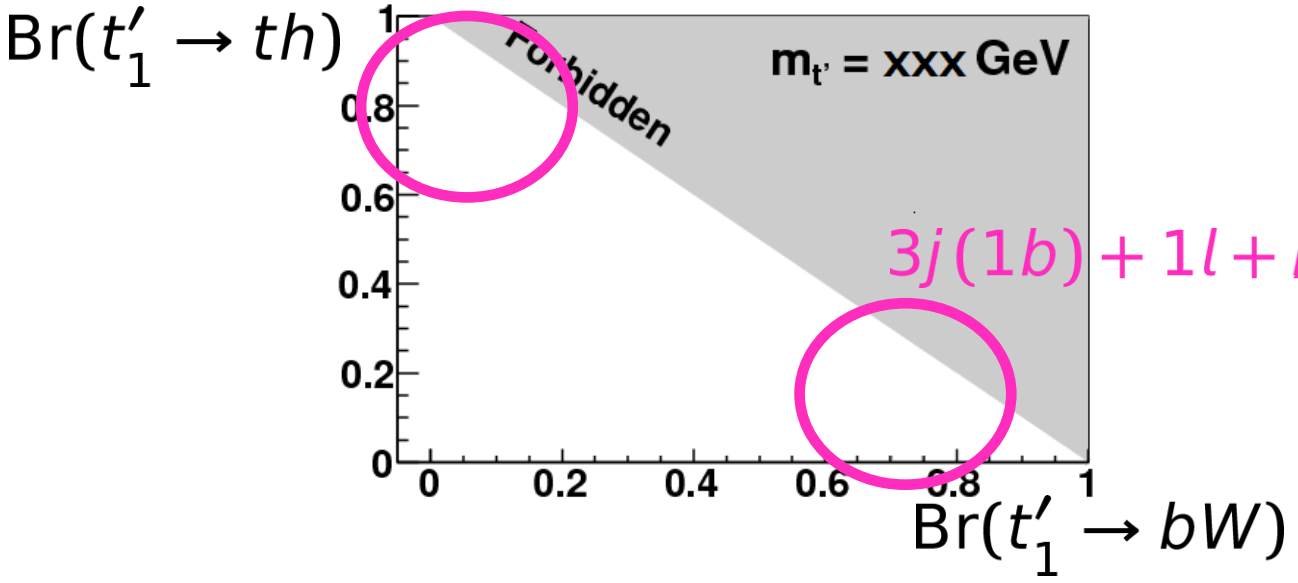
$$W_{\text{mix}} = \epsilon_i Q_i H_u U' + \epsilon'_i Q' H_u \bar{U}_i + \epsilon''_i Q' H_d \bar{D}_i + \epsilon^L_i L_i H_d \bar{E}'$$

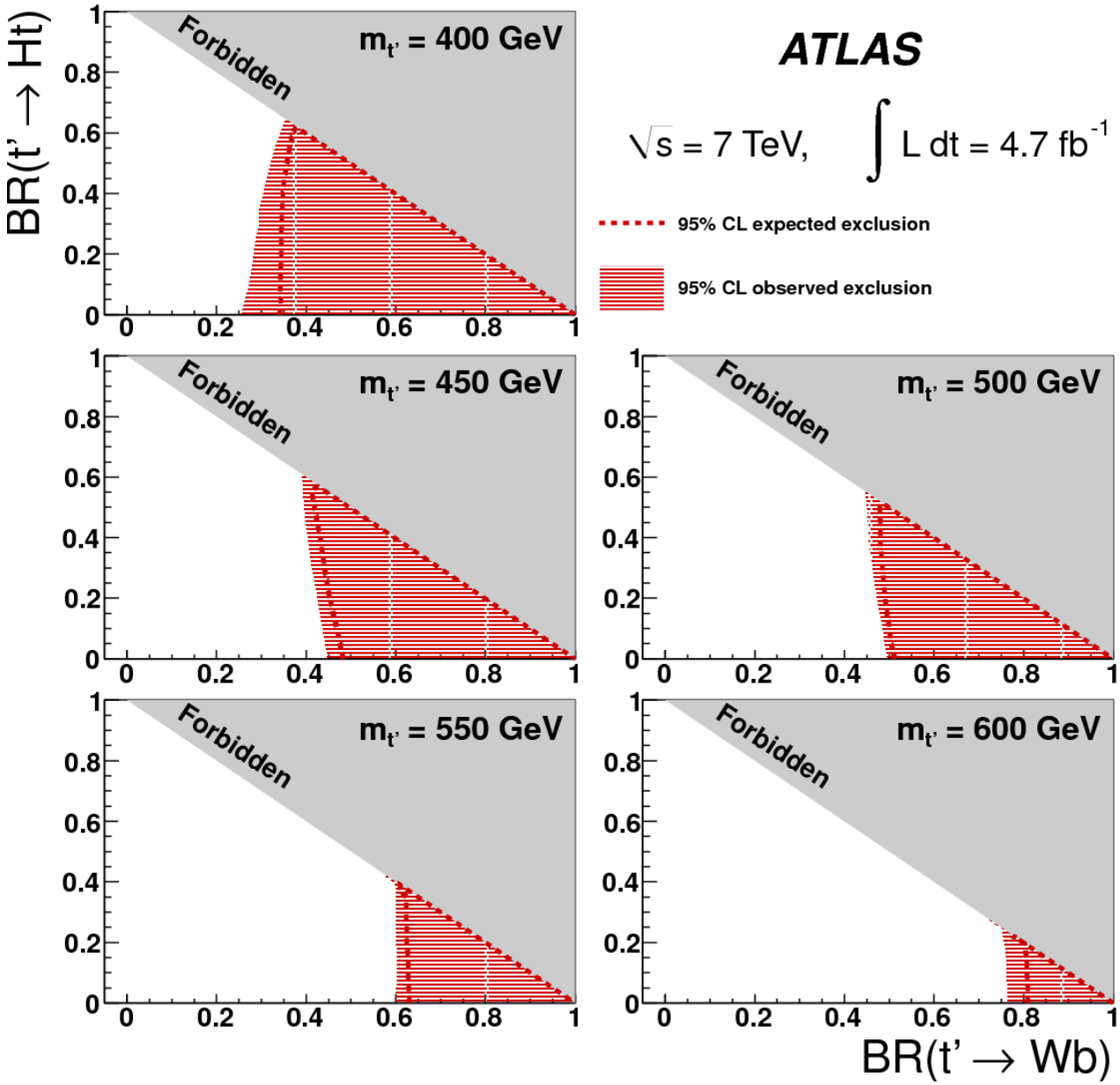
- Assumption: mixing with **3-gen.** only. ($\epsilon_1 = \epsilon_2 = 0$) etc.

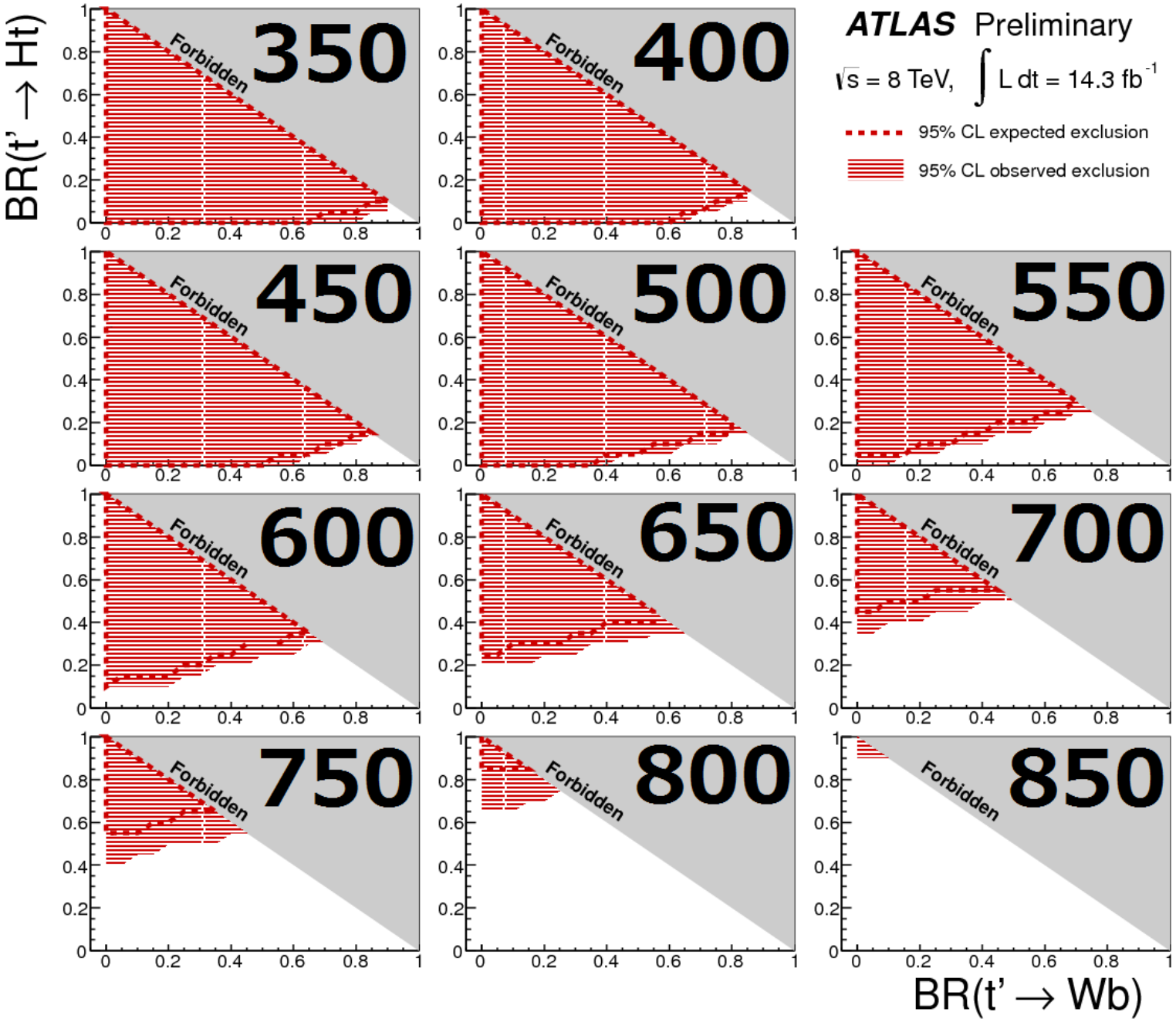
$t'_1 \to bW$, tZ, th $\times 2$ (pair-prod.)

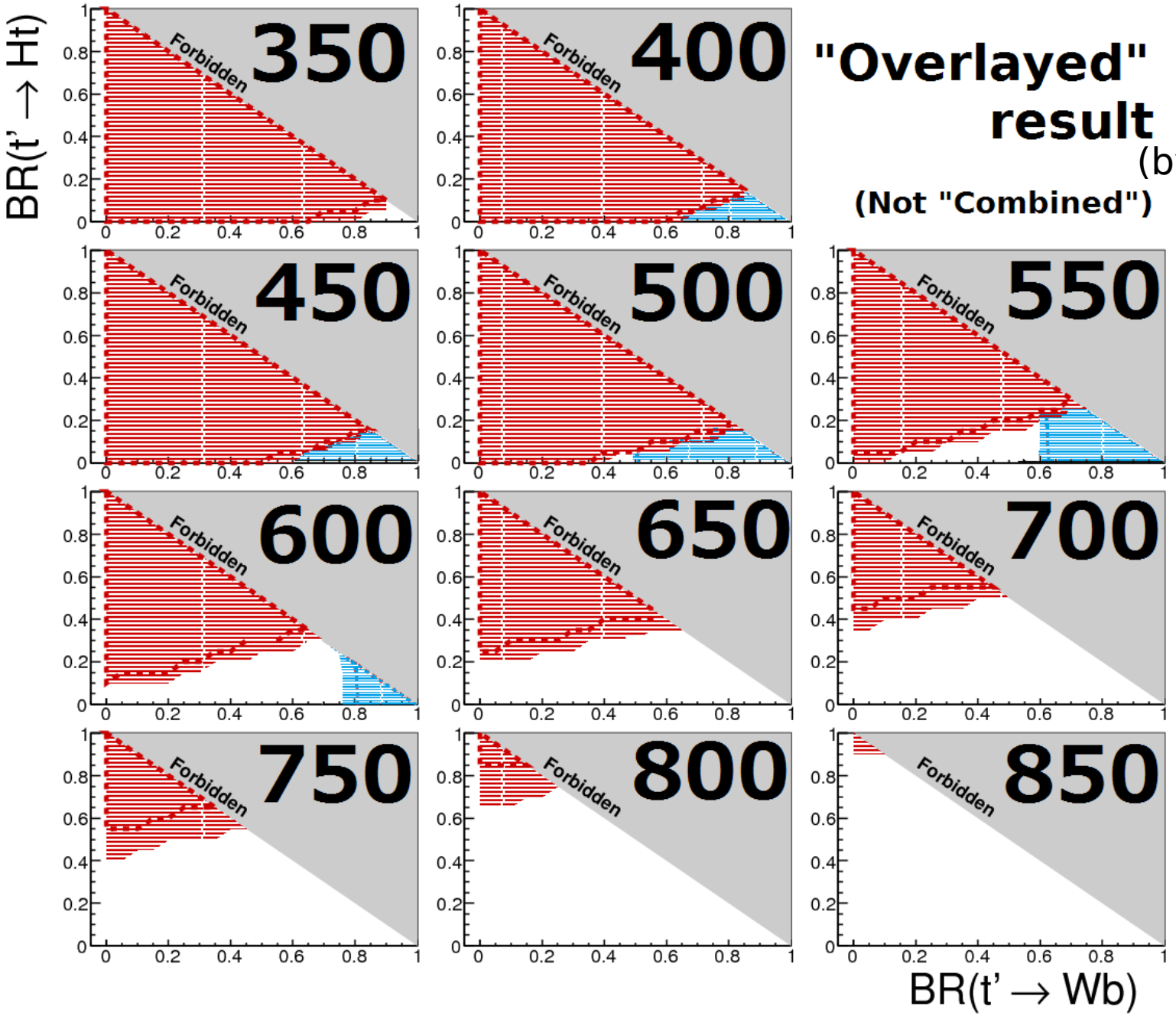
- $\to$ b-jet + (0–2)leptons ← Analyzed by ATLAS!!
- $\to$ b-jet + many leptons
- $\to$ many b-jets ← Analyzed by ATLAS!!

$6j\,(2\text{–}4b) + 1l + \not{E}_T$




ATLAS
√s = 7 TeV, ∫ L dt = 4.7 fb-1
95% CL expected exclusion
95% CL observed exclusion
BR(t' → Ht)
BR(t' → Wb)
Forbidden
mt' = 400 GeV
mt' = 450 GeV
mt' = 500 GeV
mt' = 550 GeV
mt' = 600 GeV


ATLAS Preliminary
√s = 8 TeV, ∫ L dt = 14.3 fb-1
95% CL expected exclusion
95% CL observed exclusion
BR(t' → Ht)
BR(t' → Wb)
Forbidden
350
400
450
500
550
600
650
700
750
800
850

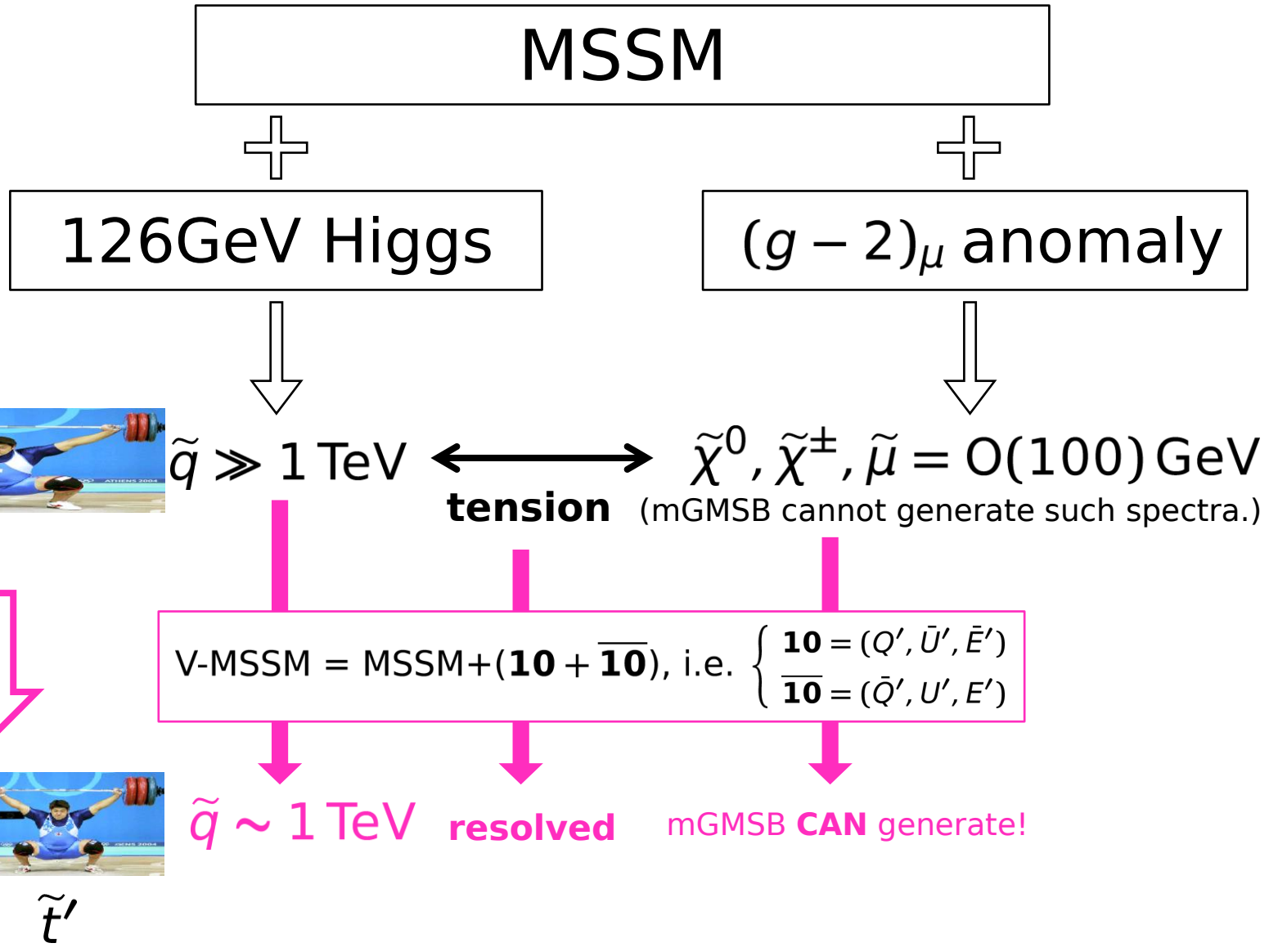


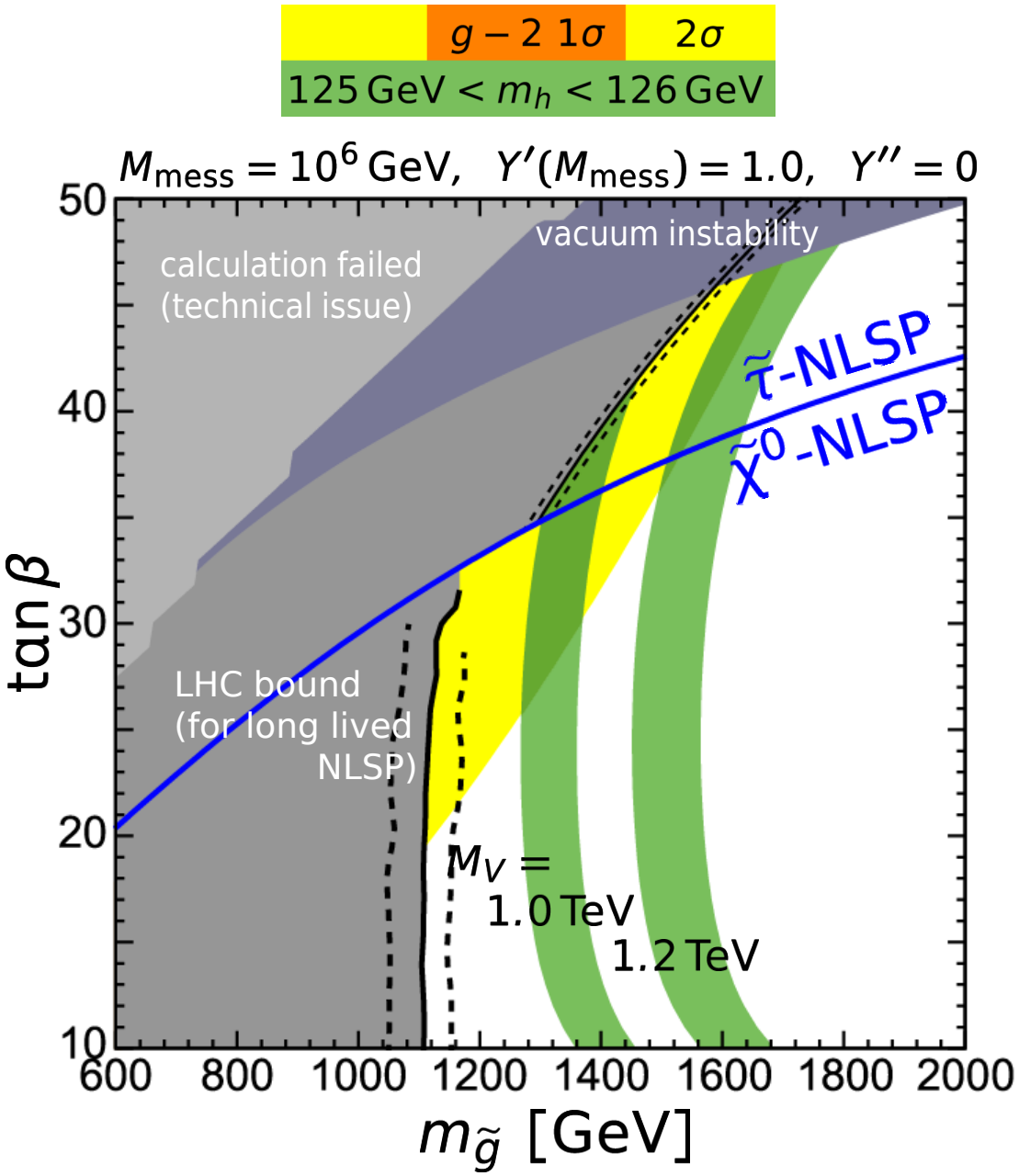
"Overlayed" result
(by myself)
(Not "Combined")

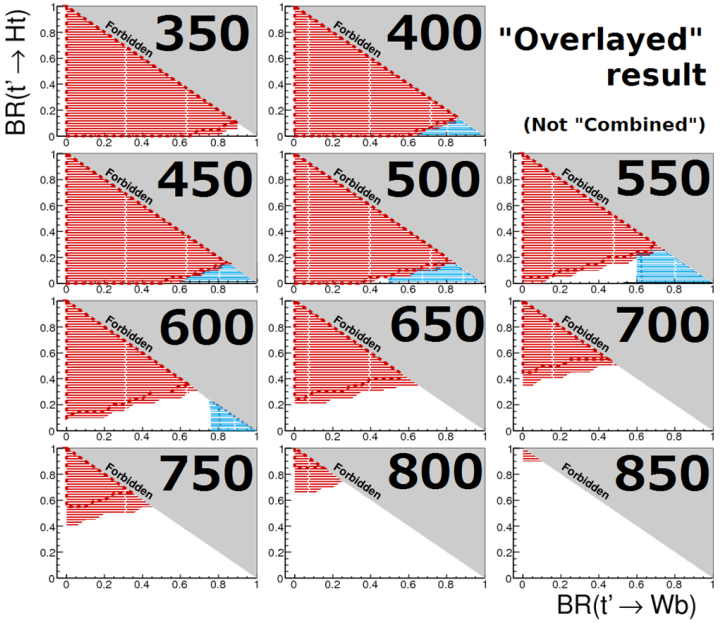
- Topic 2.

$\tilde{t}$

$\tilde{t}$ $\tilde{t}'$




$g-2$ 1σ
2σ
$125\,\mathrm{GeV} < m_h < 126\,\mathrm{GeV}$
$M_{\mathrm{mess}} = 10^6\,\mathrm{GeV},\quad Y'(M_{\mathrm{mess}}) = 1.0,\quad Y'' = 0$
calculation failed
(technical issue)
vacuum instability
$\tilde{\tau}$-NLSP
$\tilde{\chi}^0$-NLSP
LHC bound
(for long lived
NLSP)
$M_V =$
1.0 TeV
1.2 TeV
$\tan\beta$
$m_{\tilde{g}}$ [GeV]
50
40
30
20
10
600
800
1000
1200
1400
1600
1800
2000


BR(t' → Ht)
350
400
450
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650
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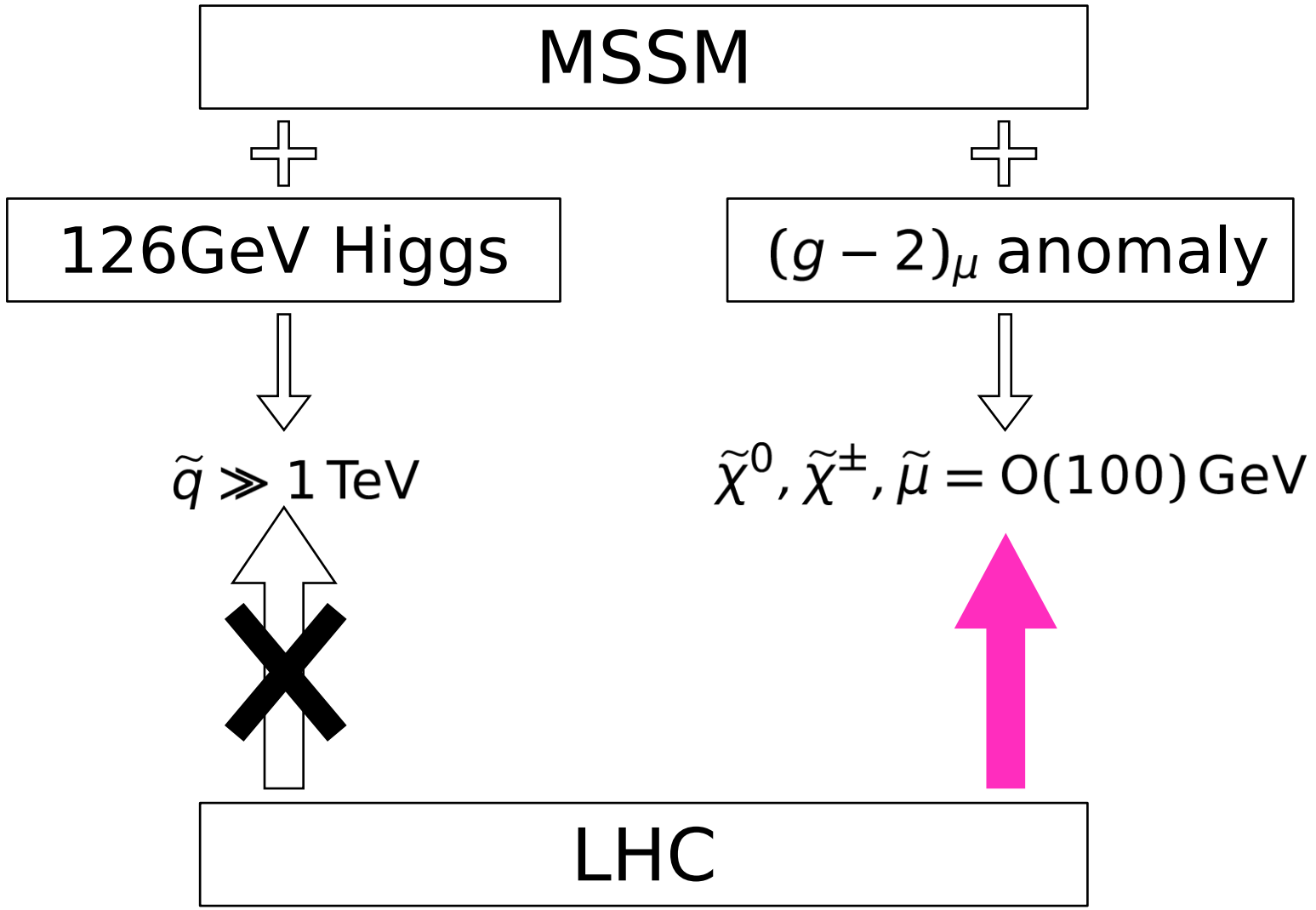
Forbidden
"Overlayed"
result
(Not "Combined")
BR(t' → Wb)

Summary?

Endo, Hamaguchi, *SI*, Yoshinaga [1303.4256]

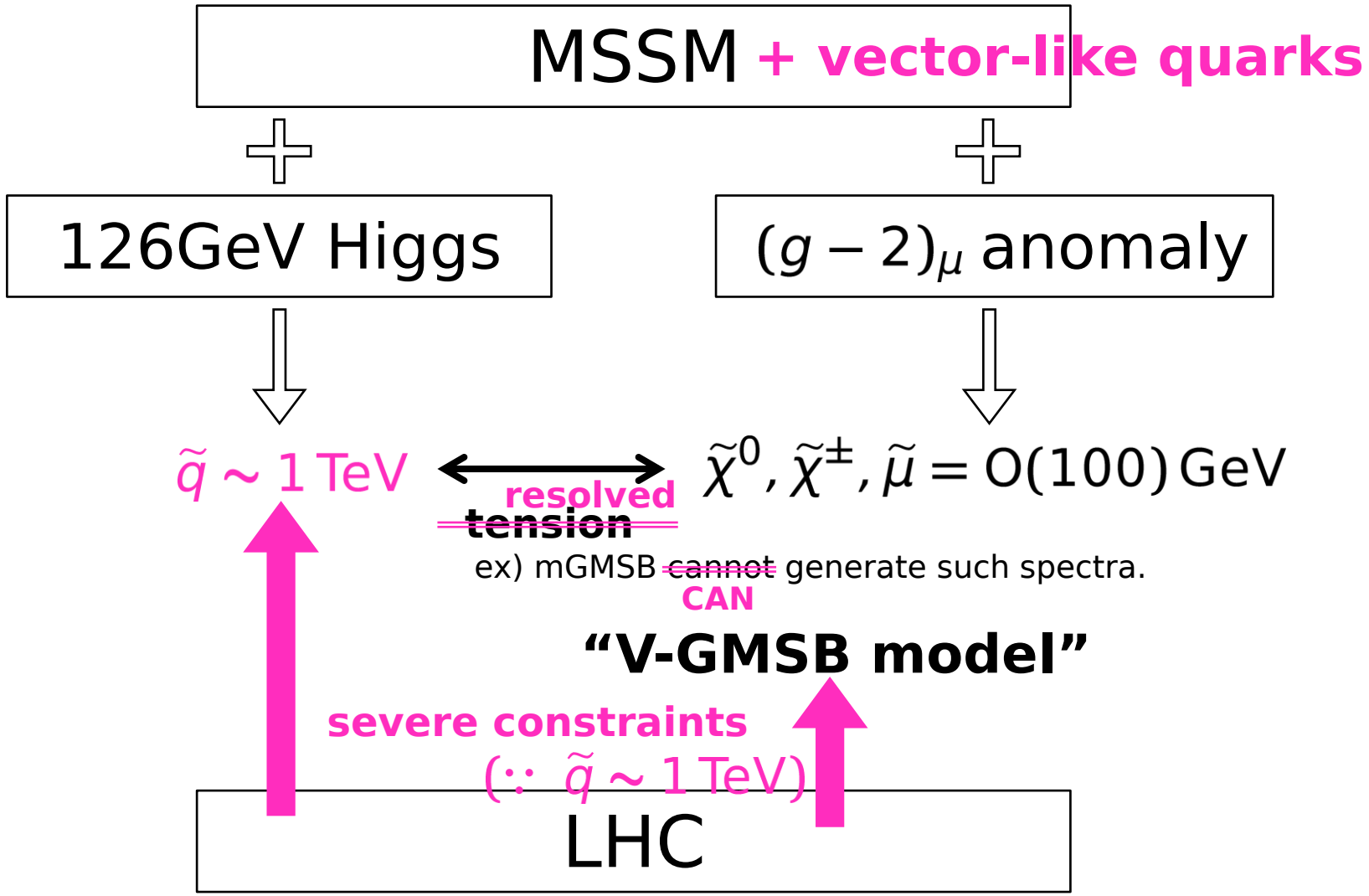
Topic 1.

(Minimal SUSY Standard Model)

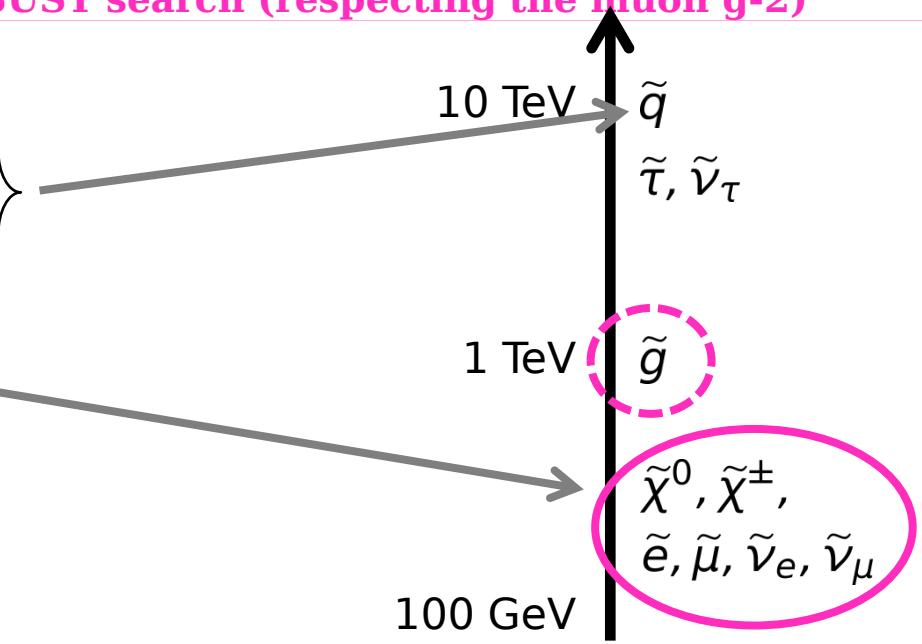


Topic 2.

(Minimal SUSY Standard Model)

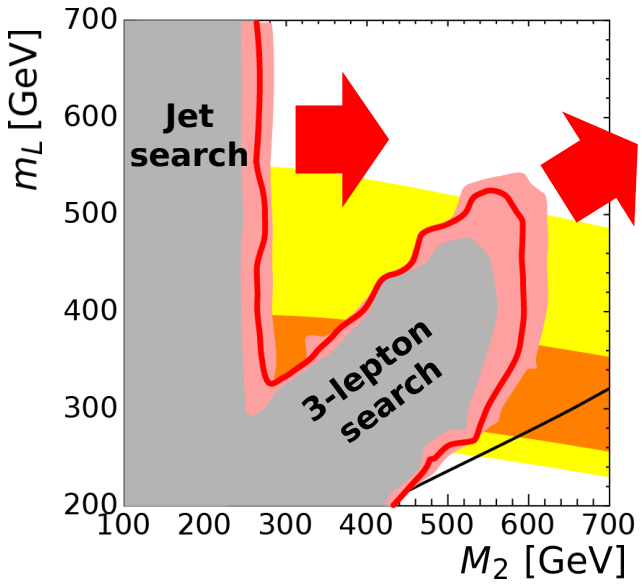


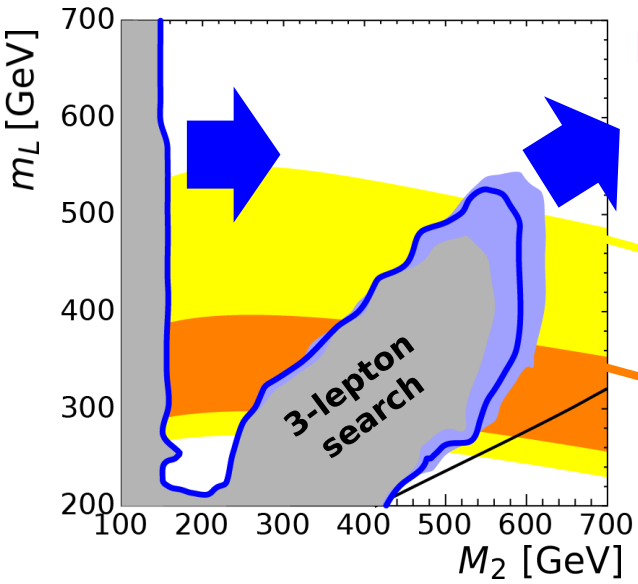
- 126 GeV Higgs
- SUSY Not Found yet
- $(g-2)_\mu$ anomaly



An extreme case: $\mu = 2\,\text{TeV}$, $m_L^2 : m_{\bar{E}}^2 = 1 : (1.5)^2$

Jet: ATLAS-CONF-2012-109
3L: ATLAS-CONF-2012-154

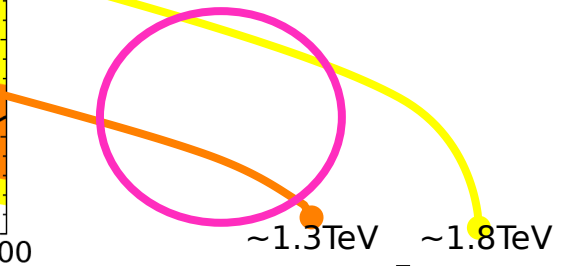


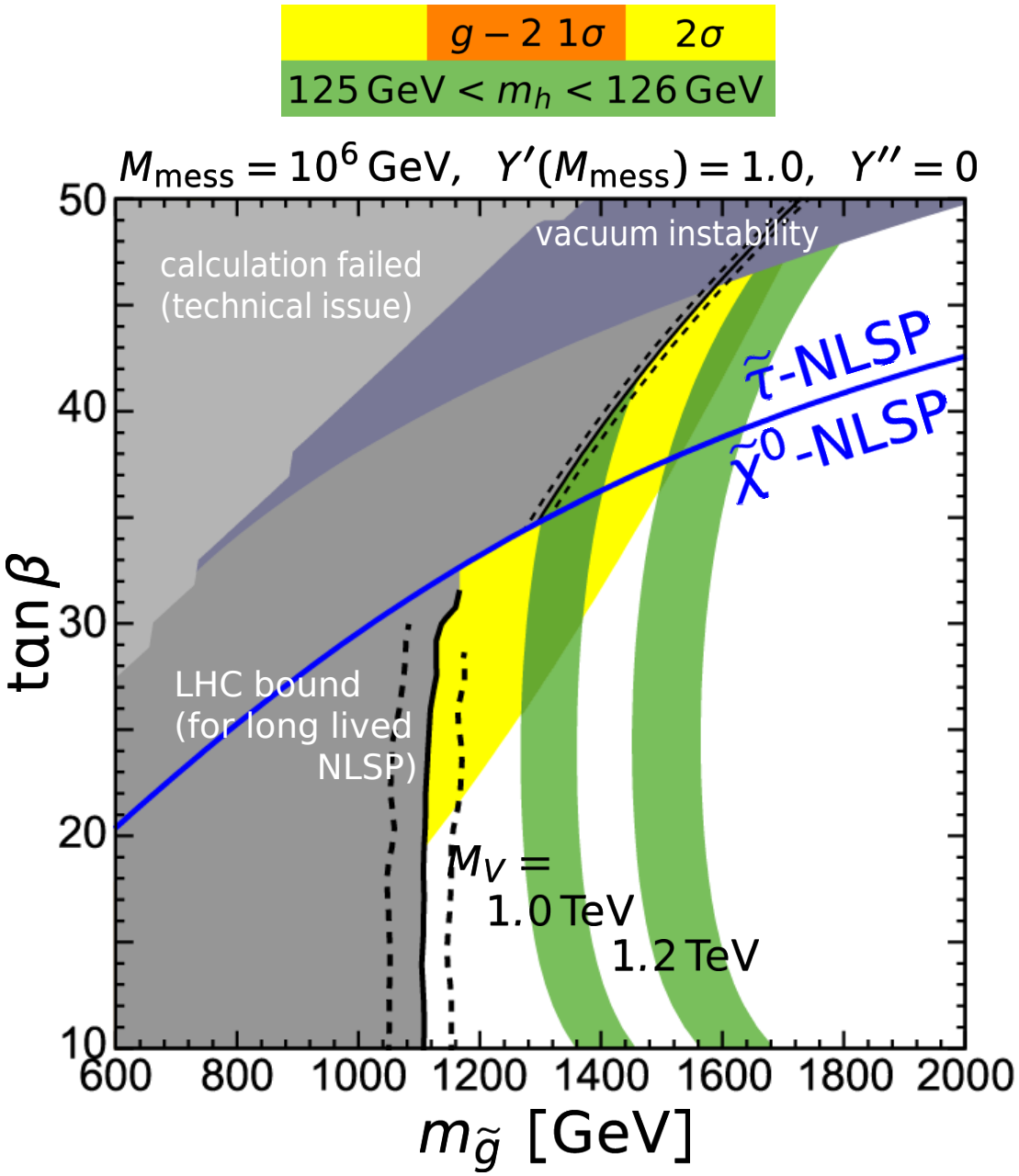


How can we search?

- Heavy gaugino
- Large μ-term
- Light sleptons

... future work.

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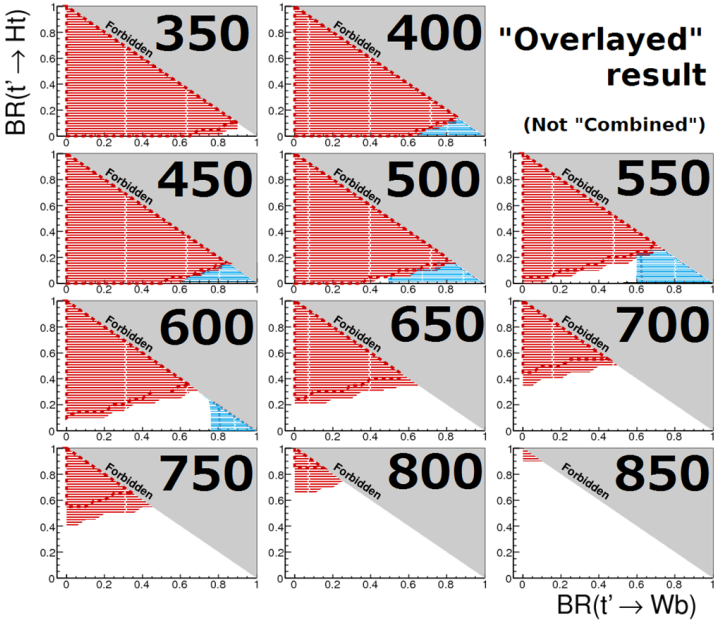
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